Top Quark Production at Hadron Colliders

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University of Manchester

on behalf of

Large Hadron Collider Physics Conference

Barcelona

17 May 2013

Outline

Introduction
Top Pair Production
Differential Cross Sections
Single Top Production
Top Pair Asymmetries
Conclusions

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Single Top Production
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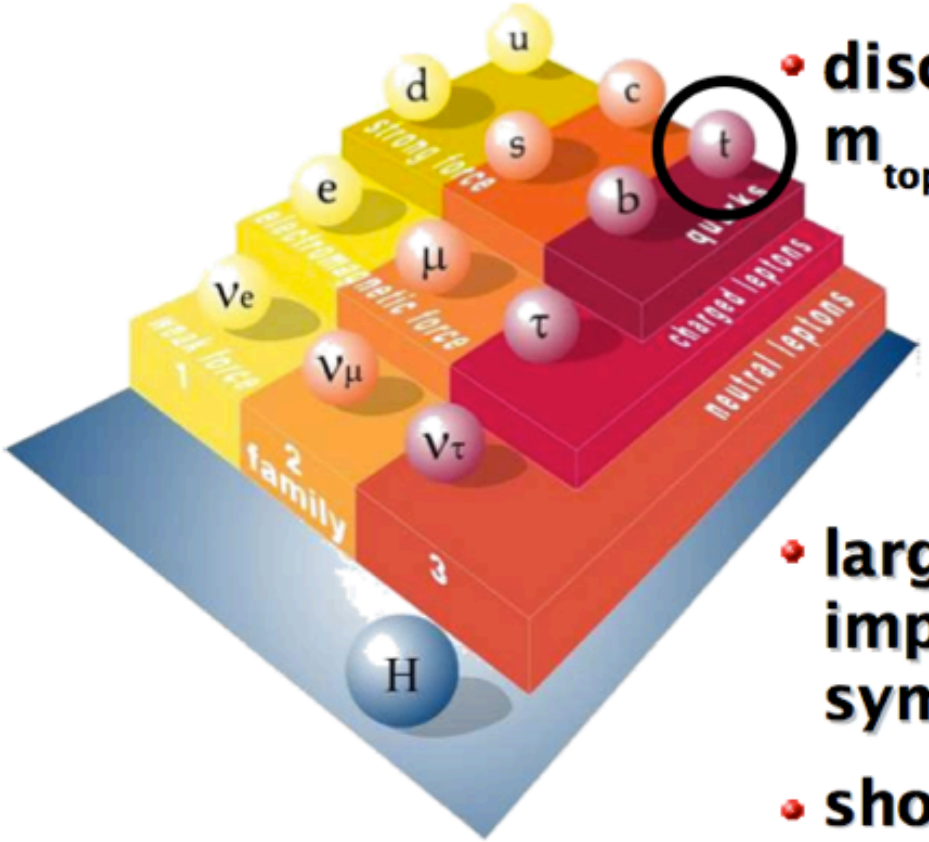
The Top Quark



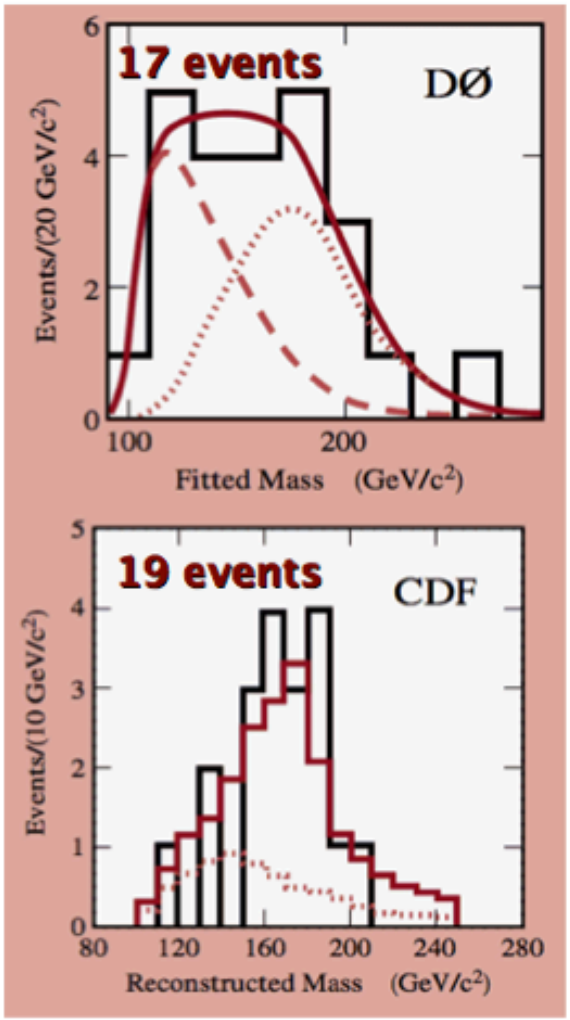
- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold nucleus
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}$s $\ll \Lambda^{-1}_{QCD}$: decays before fragmenting → observe "naked" quark

is the top quark as predicted by the SM?

The Top Quark

discovery

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

March 2nd, 1995:

First announcement of Top Discovery in public seminar at Fermilab

The Top Quark

discovery

PRL 74, 2632 (1995)
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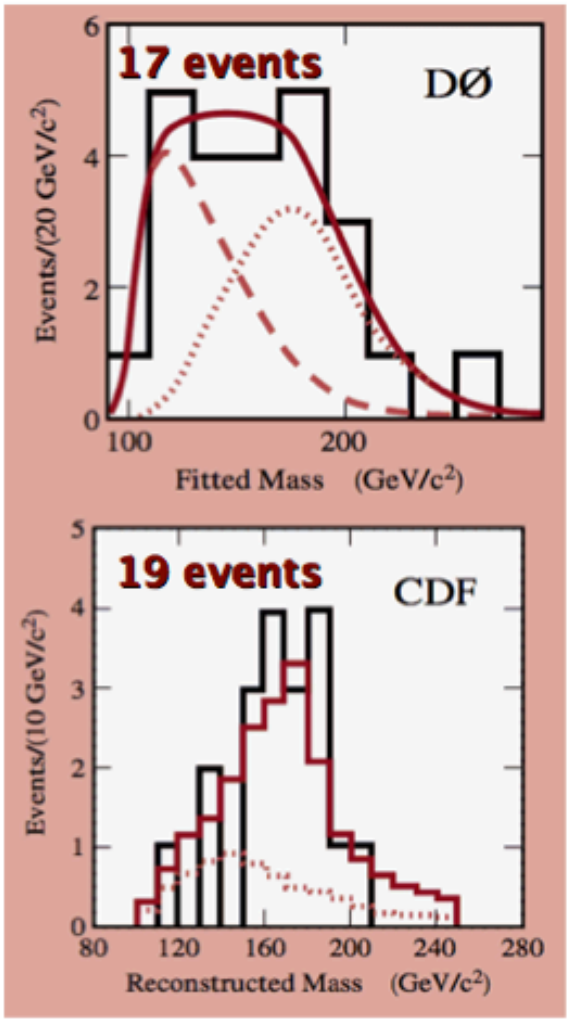
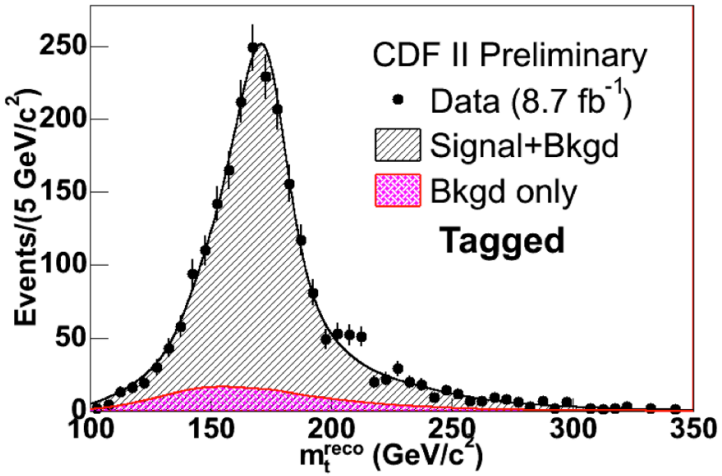


1995, CDF and DØ experiments, Fermilab

today

1000s of events



The Top Quark

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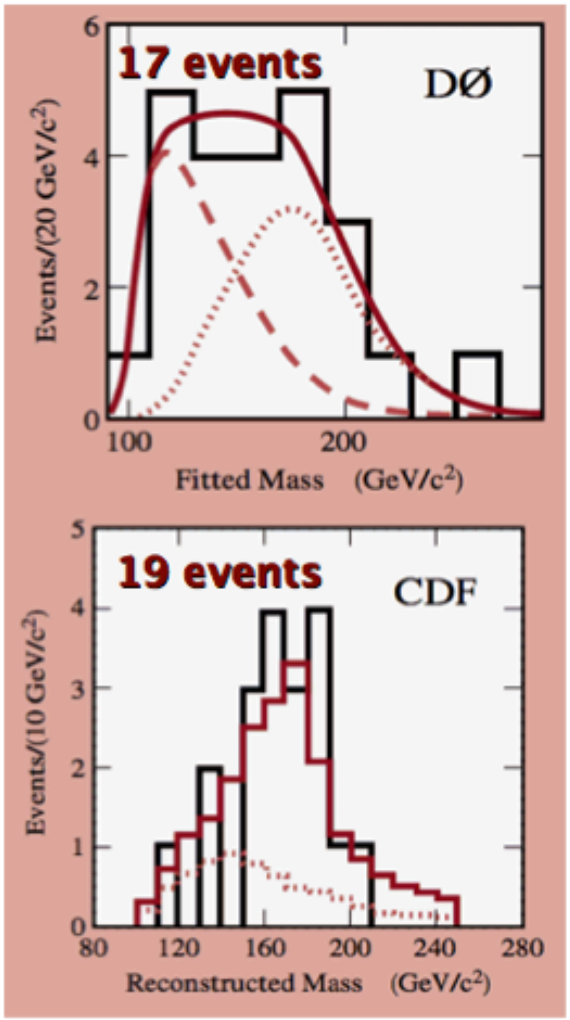

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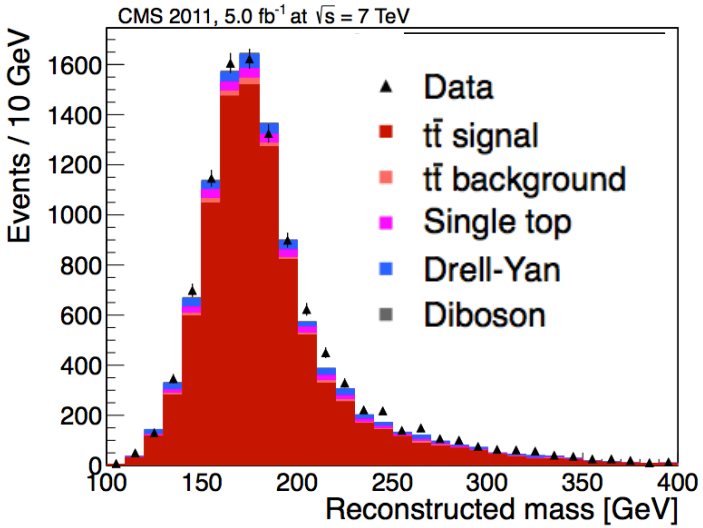


LHC: top quark factory

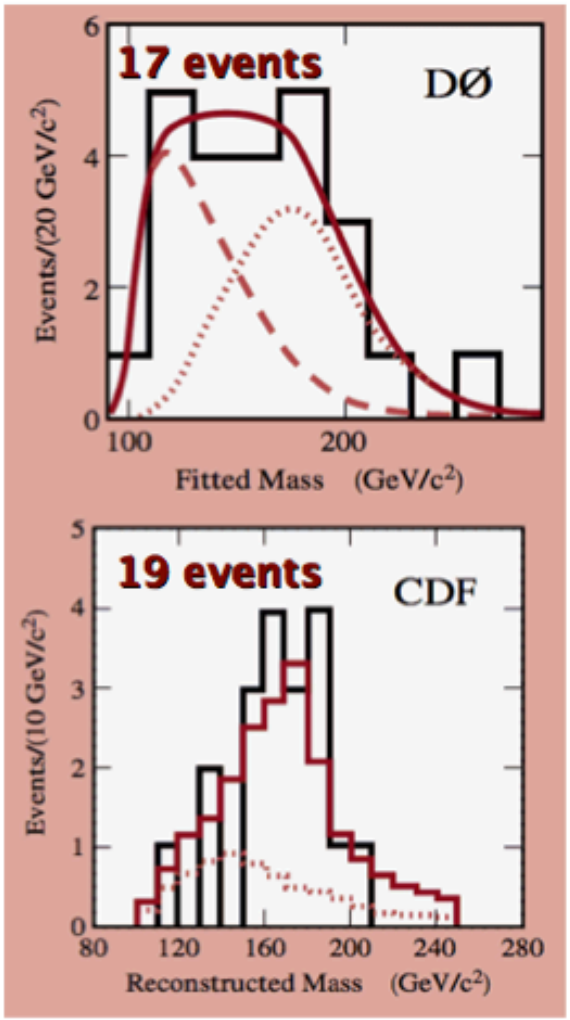
The Top Quark

discovery

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)

María José Costa

precision



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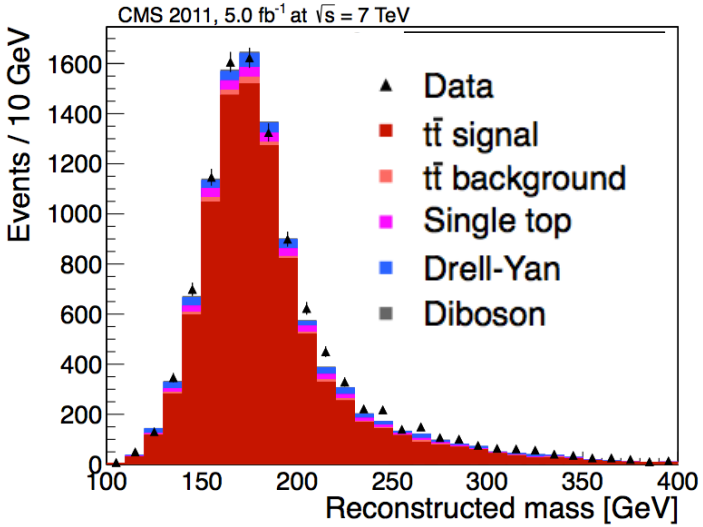

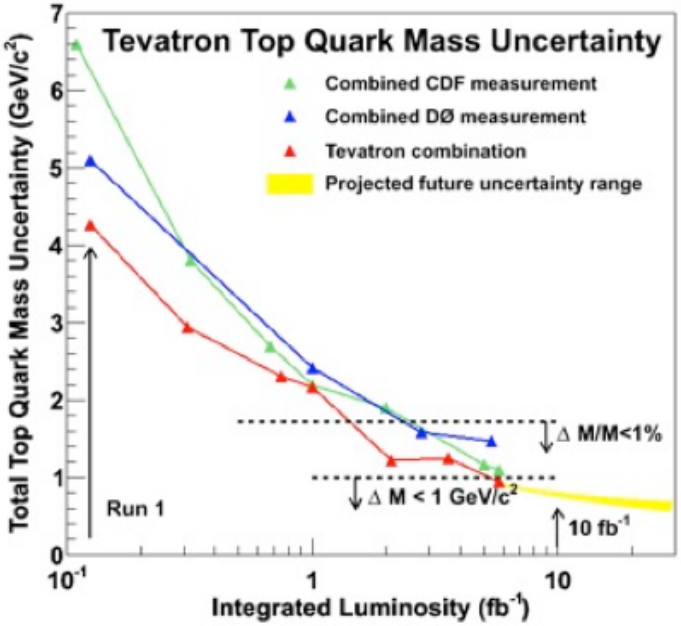

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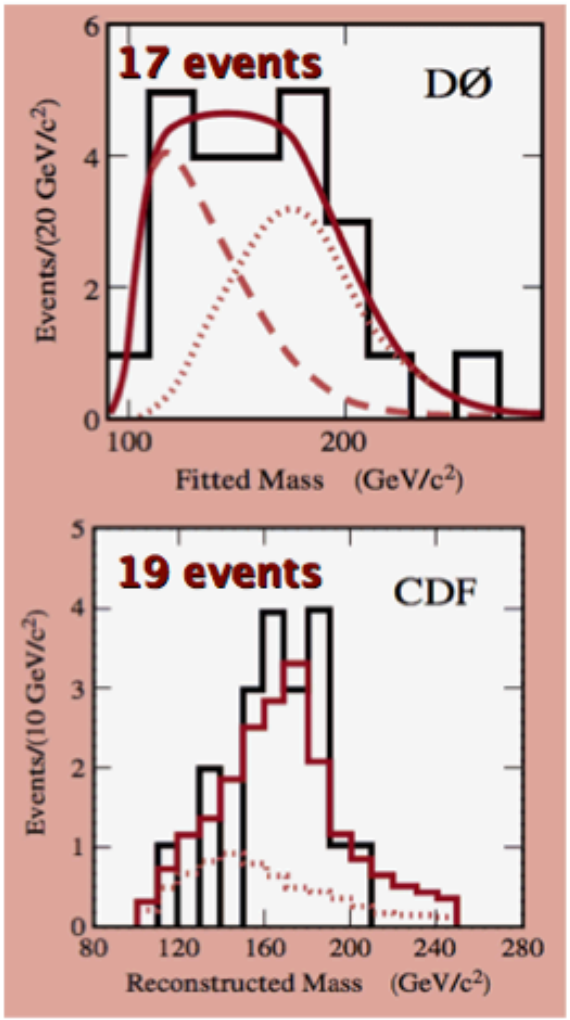

1995, CDF and DØ experiments, Fermilab

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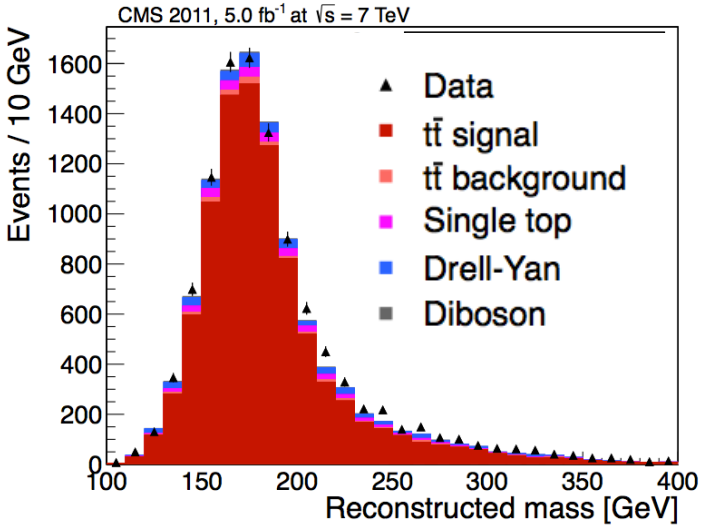

LHC: top quark factory

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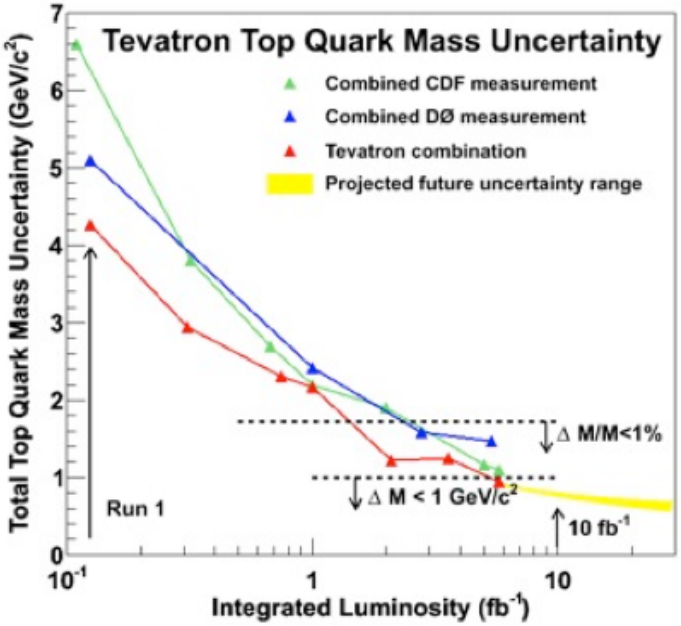

searches

Justin Pilot

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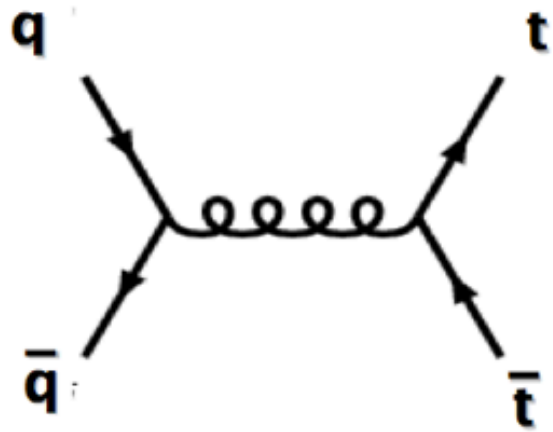
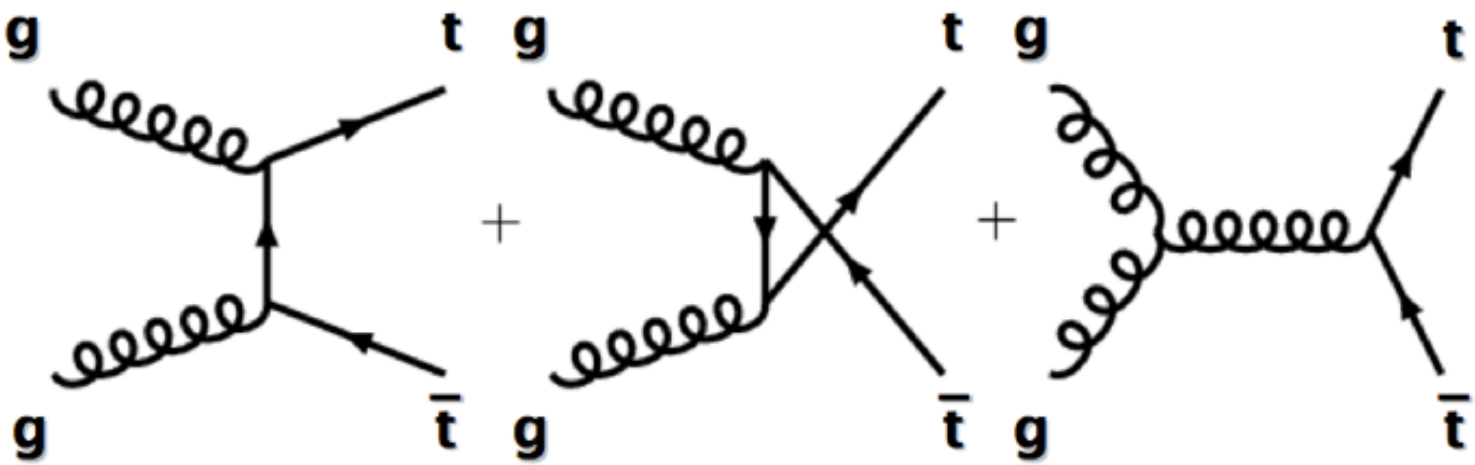
Top Quark Pair Production



Tevatron (~85%)



LHC (~87%)
(8 TeV)

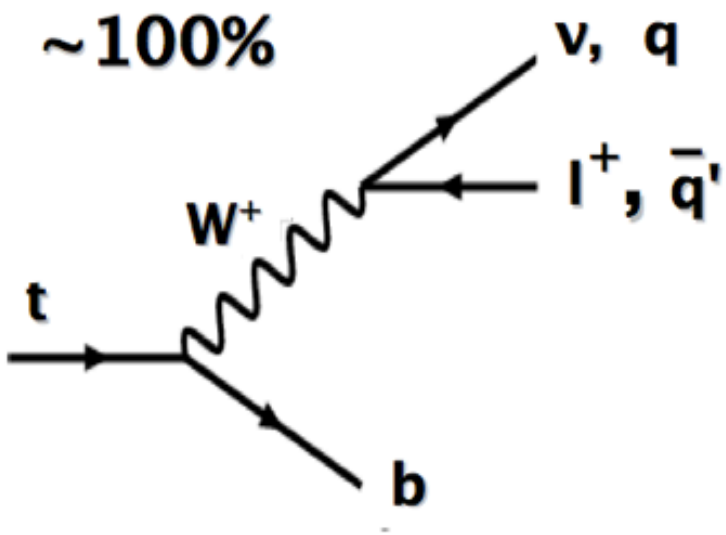
Top Quark Pair Signatures

τ's 14%

alljets 46%

top decay:

~100%



- high p_T leptons, missing E_T
- jets
- b-jets

Top Pair Decay Channels

W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
$\bar{c}s$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{u}d$					
τ^-	eτ	μτ	ττ	tau+jets	
μ^-	eμ	μμ	μτ	muon+jets	
e^-	ee	eμ	eτ	electron+jets	

dileptons

dilepton (e/μ) 6%

e/μ+jets 34%

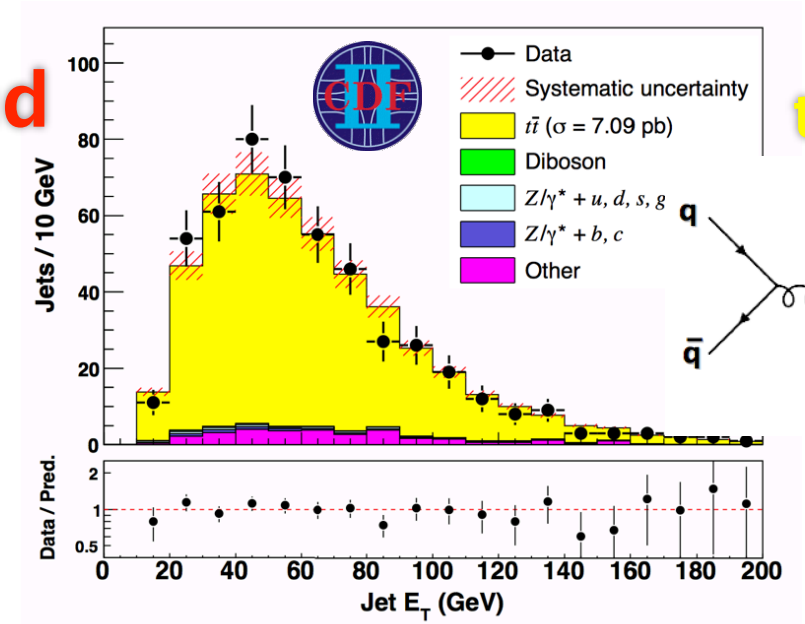
Lepton+Jets Topological Cross Section

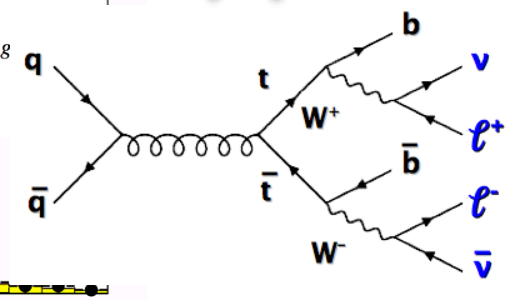
powerful test of QCD and search for new physics!

for separation between signal and background use variables such as:

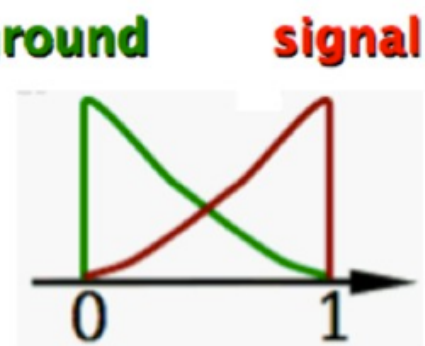
energy-dependent quantities:
e.g. lepton transverse energy

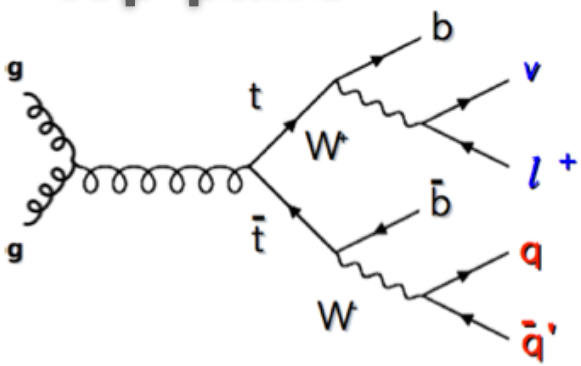
angular dependent:
e.g. pseudorapidity, aplanarity

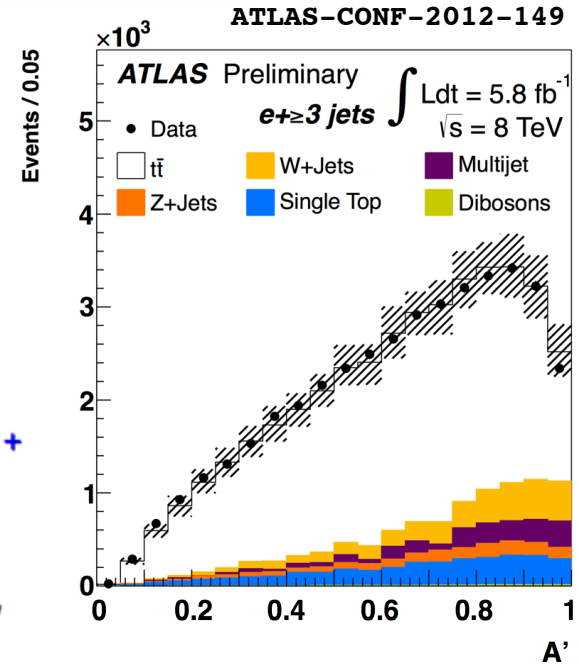




Likelihood Discriminant





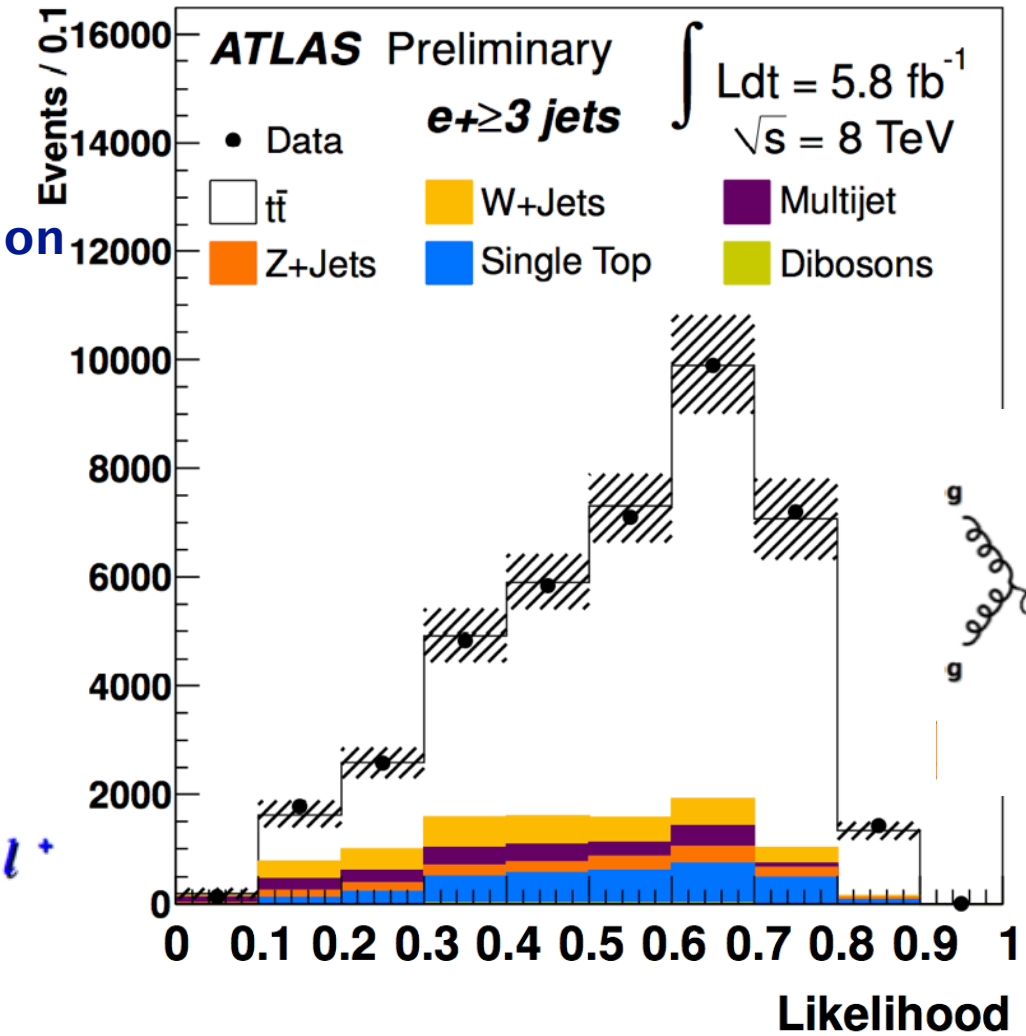


Lepton+Jets Cross Section

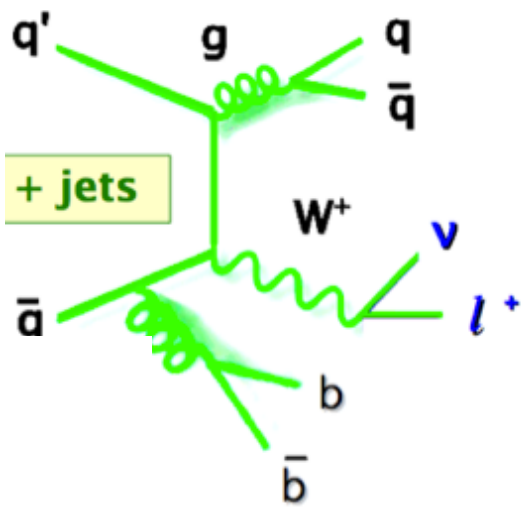
ATLAS-CONF-2012-149

main systematics:

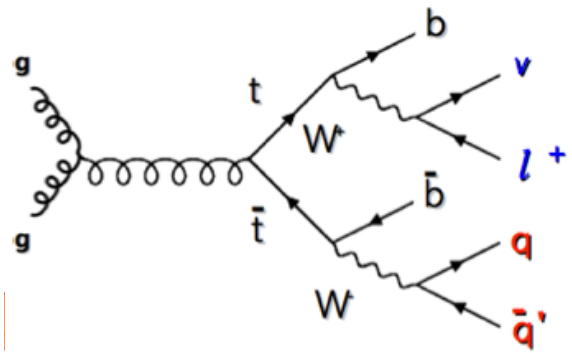
- signal modelling
- jet/MET reconstruction



W+jets



top pairs

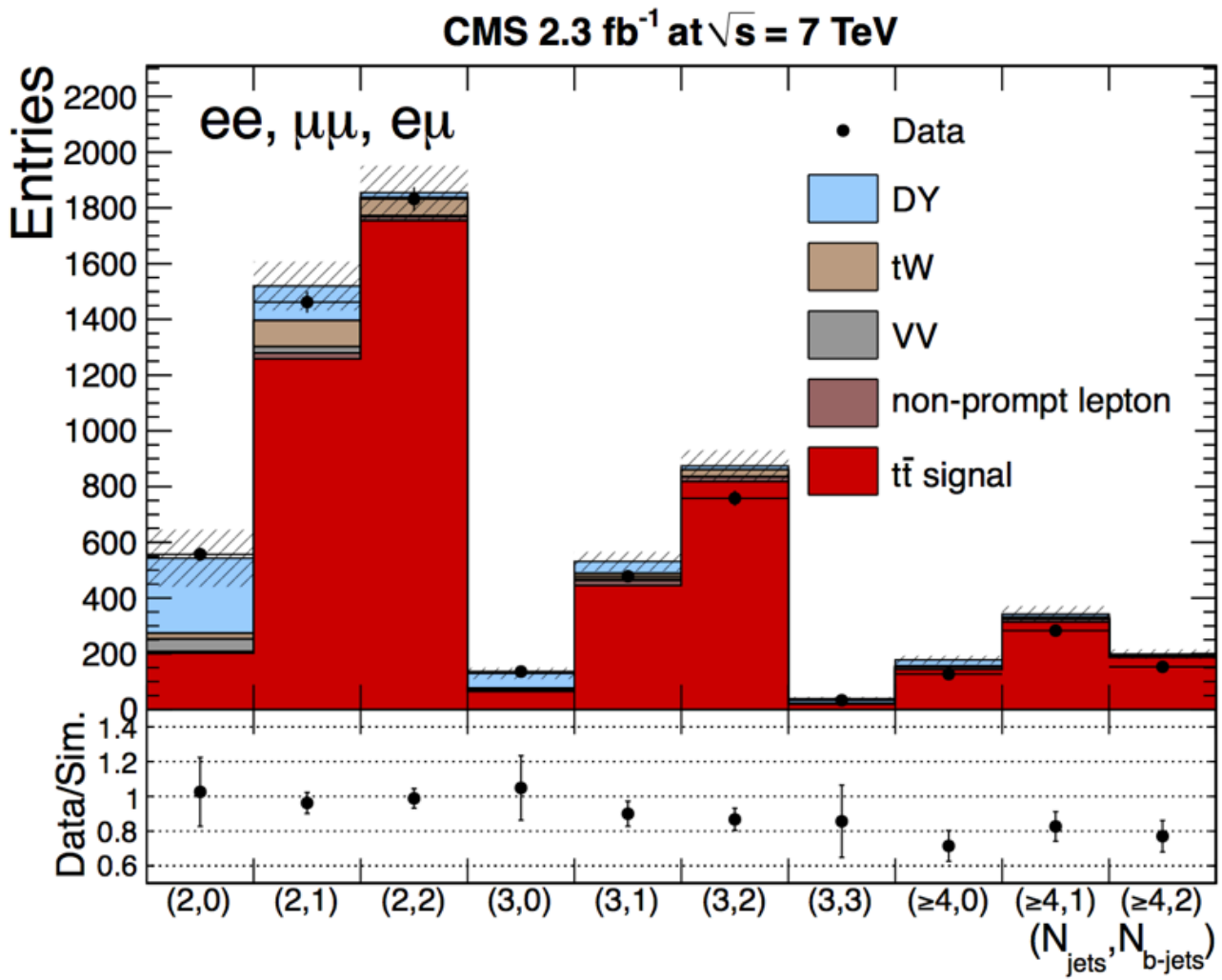


$$\sigma_{t\bar{t}} = 241 \pm 2\,(\text{stat.}) \pm 31\,(\text{syst.}) \pm 9\,(\text{lumi.})\ \text{pb}$$

±13%

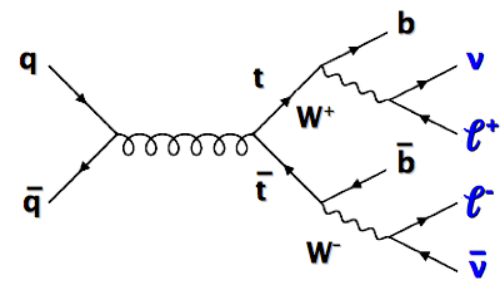
Dilepton Cross Section

JHEP 11 067 (2012)

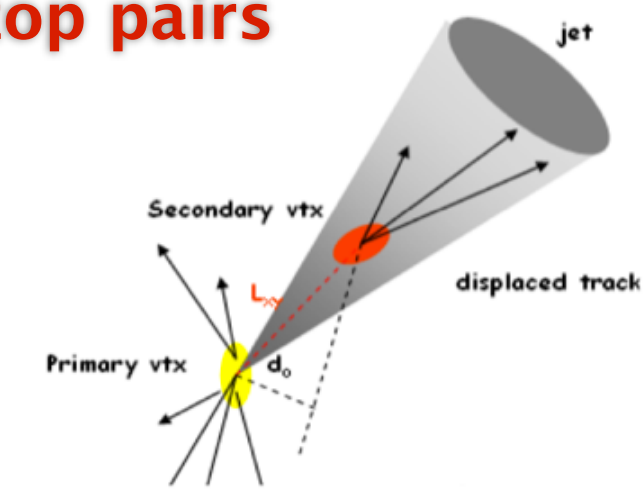


main systematics:

- jet energy scale
- W branching fraction
- lepton efficiencies



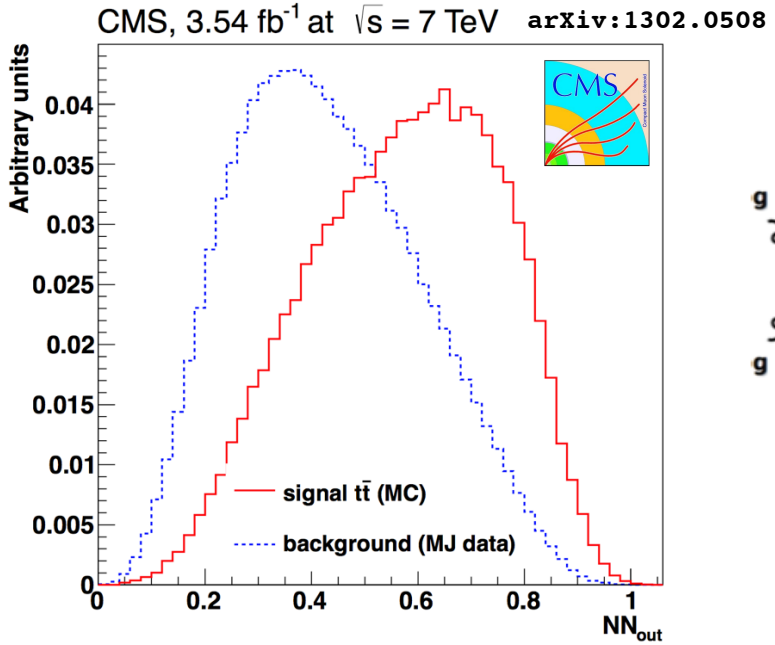
top pairs



$$\sigma_{t\bar{t}} = 161.9 \pm 2.5\,(\text{stat.})\,^{+5.1}_{-5.0}\,(\text{syst.}) \pm 3.6\,(\text{lumi.})\,\text{pb}$$

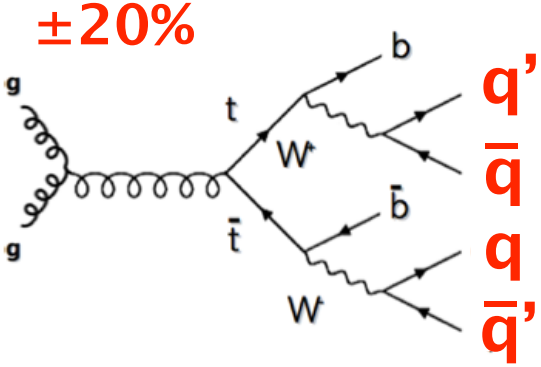
±4%

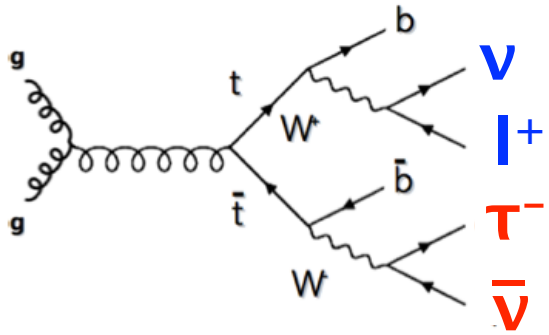
Top pair cross section in other channels



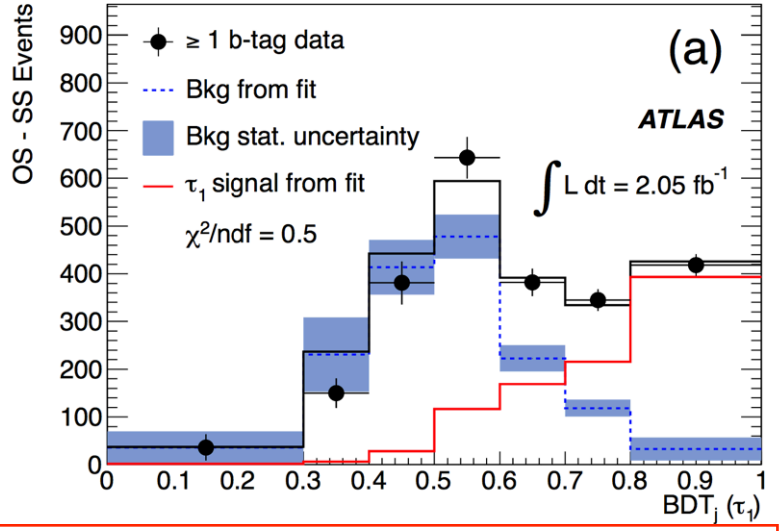
$\sigma_{t\bar{t}} = 139 \pm 10\,(\text{stat.}) \pm 26\,(\text{syst.}) \pm 3\,(\text{lum.})\,\text{pb}$

±20%





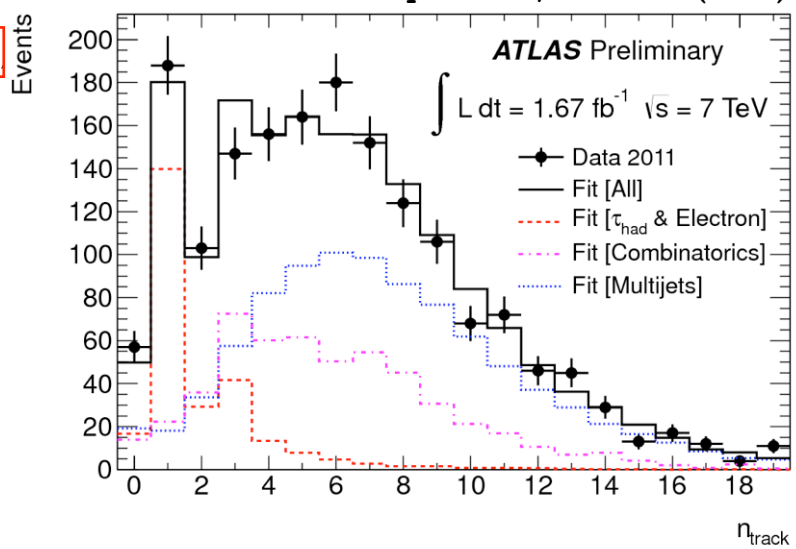
PLB 717 89 (2012)



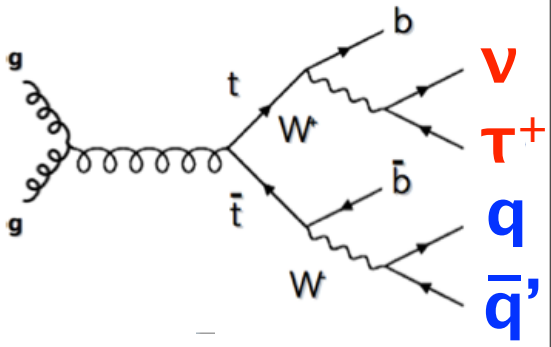
$\sigma_{t\bar{t}} = 186 \pm 13(\text{stat.}) \pm 20(\text{syst.}) \pm 7(\text{lumi.})\text{pb}$

±13%

Eur. Phys. J. C, 73 2328 (2013)

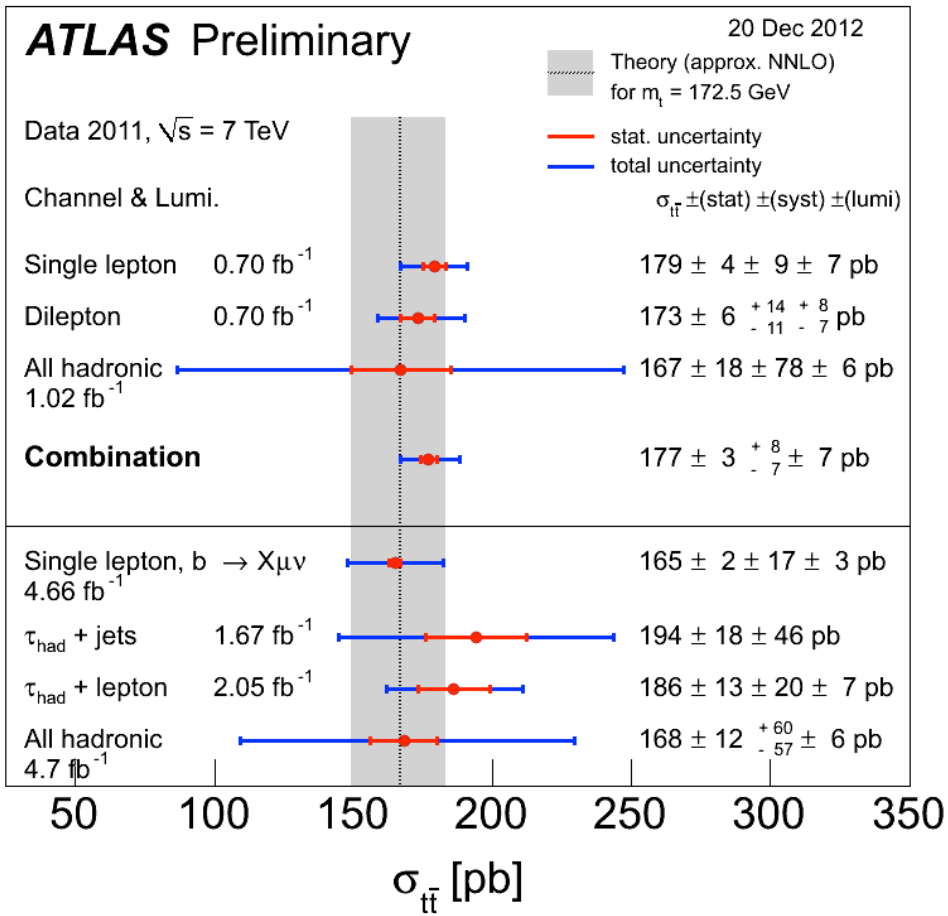


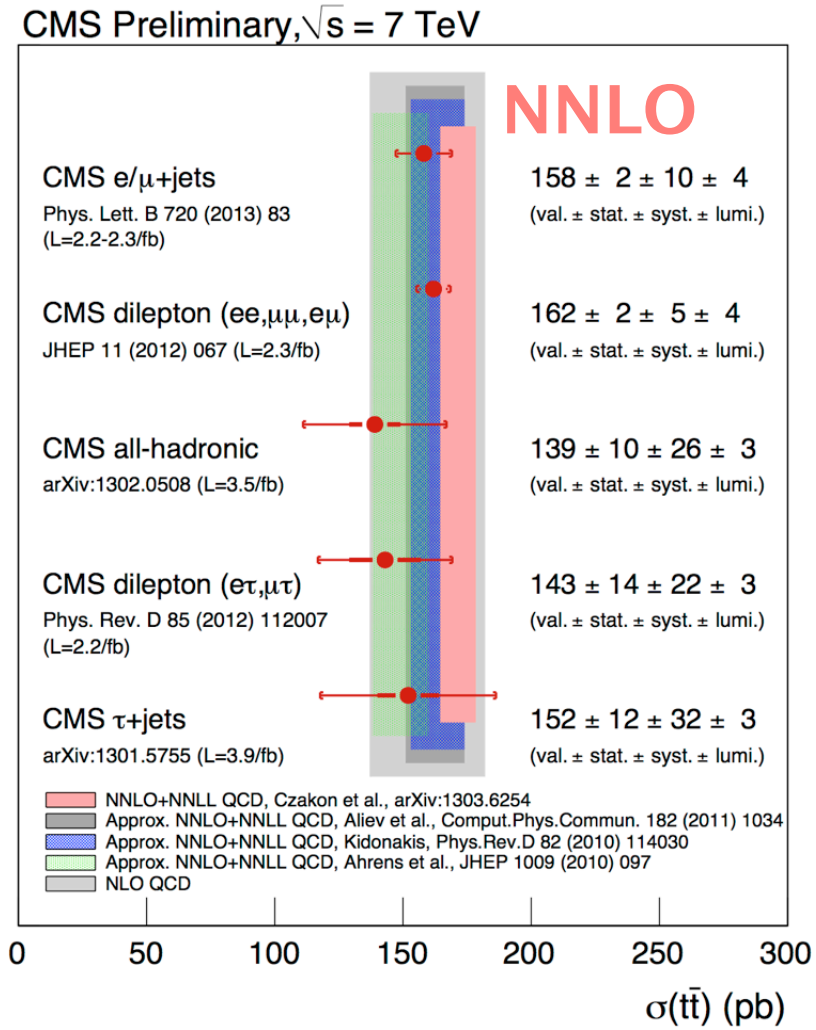
$\sigma_{t\bar{t}} = 194 \pm 18(\text{stat.}) \pm 46(\text{syst.})\text{pb}$



±25%

Top Pair Production Cross Section

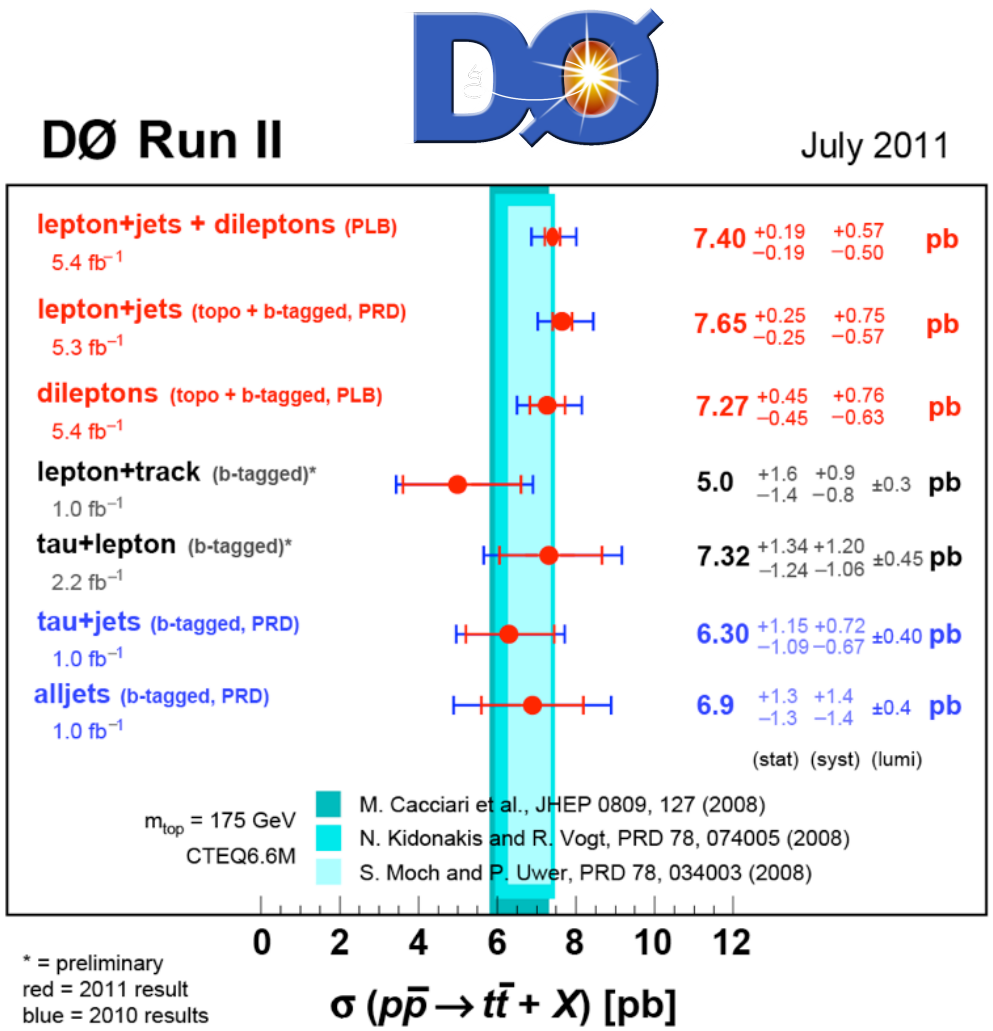


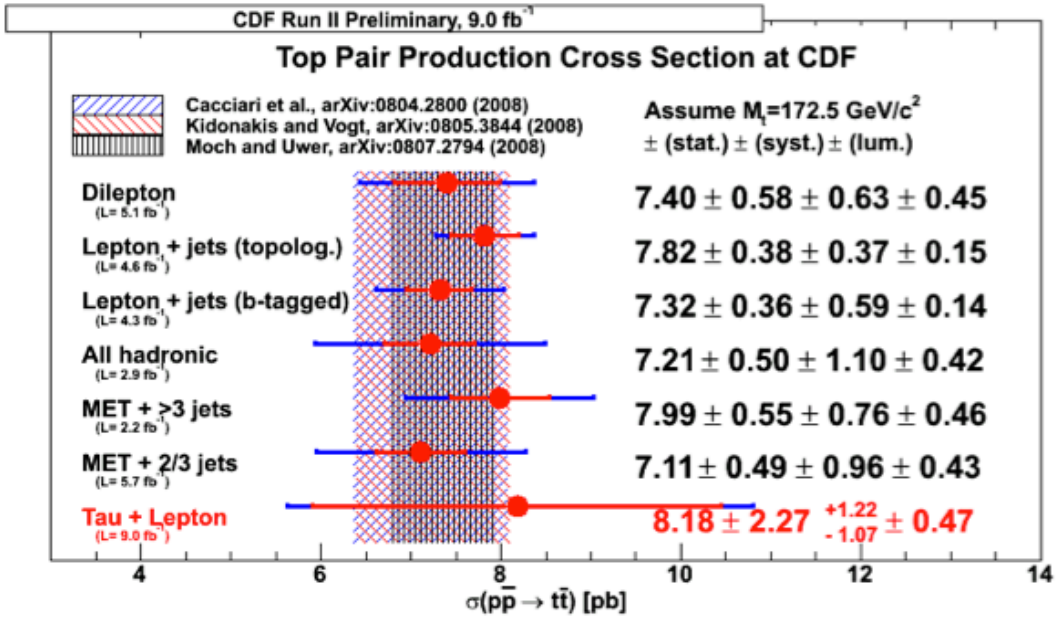


all channels measured except for τ_{had} τ_{had}

⇒ good agreement with SM in all channels

Top Pair Production Cross Section





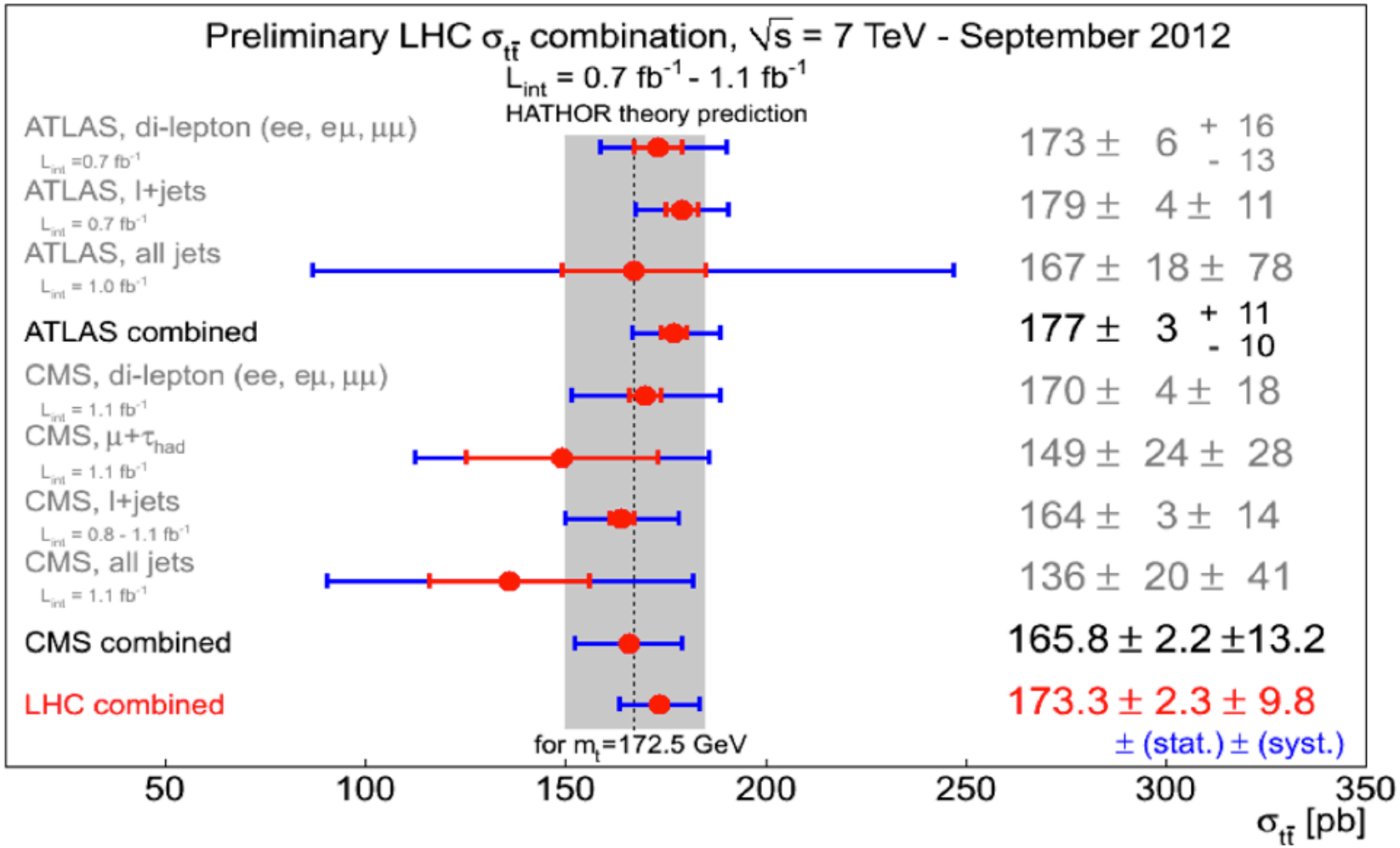
all channels measured except for $\tau_{had}\ \tau_{had}$

⇒ good agreement with SM in all channels

Top Pair Production Cross Section

ATLAS-CONF-2012-134

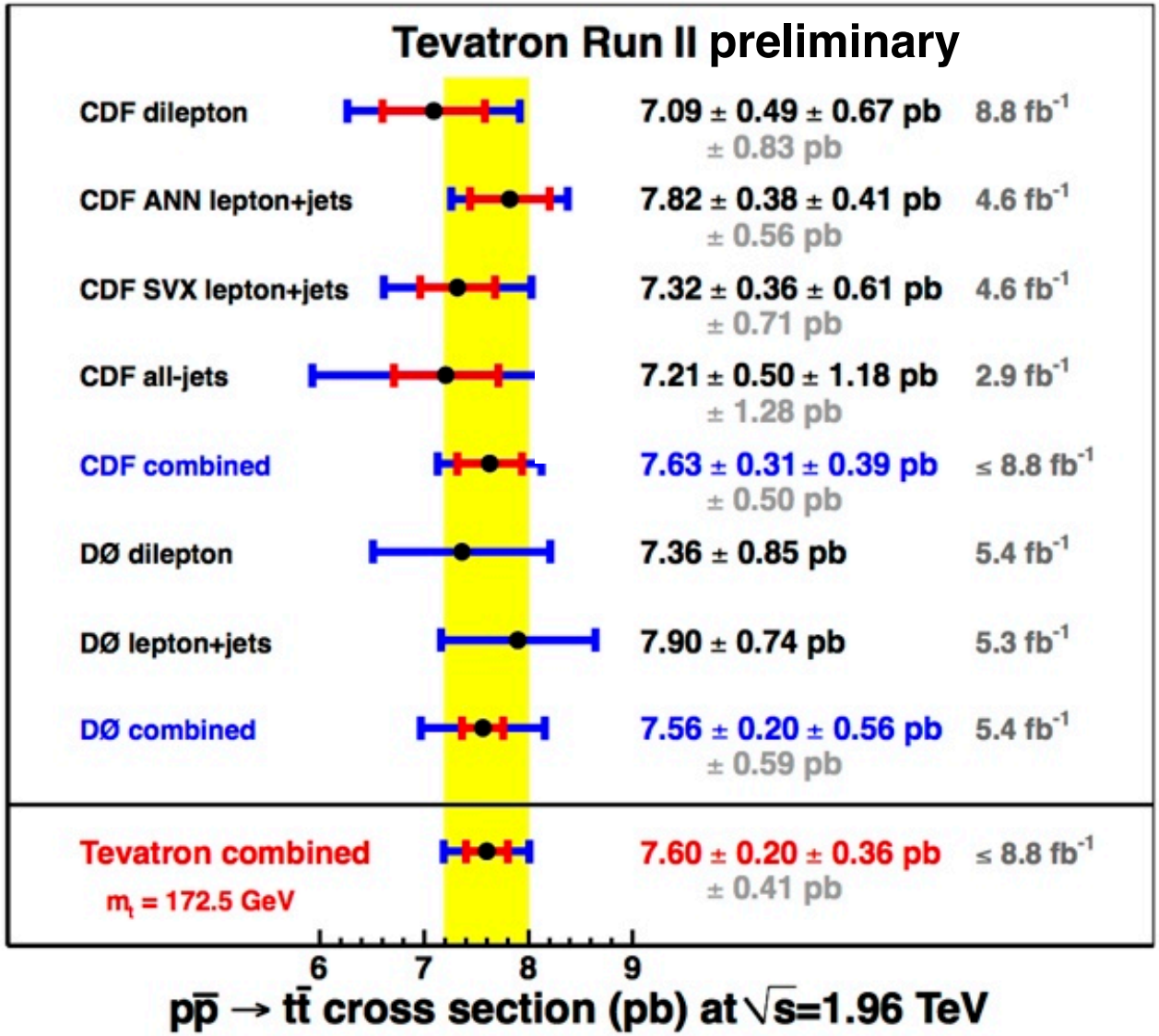
CMS PAS TOP-12-003



±5.8%

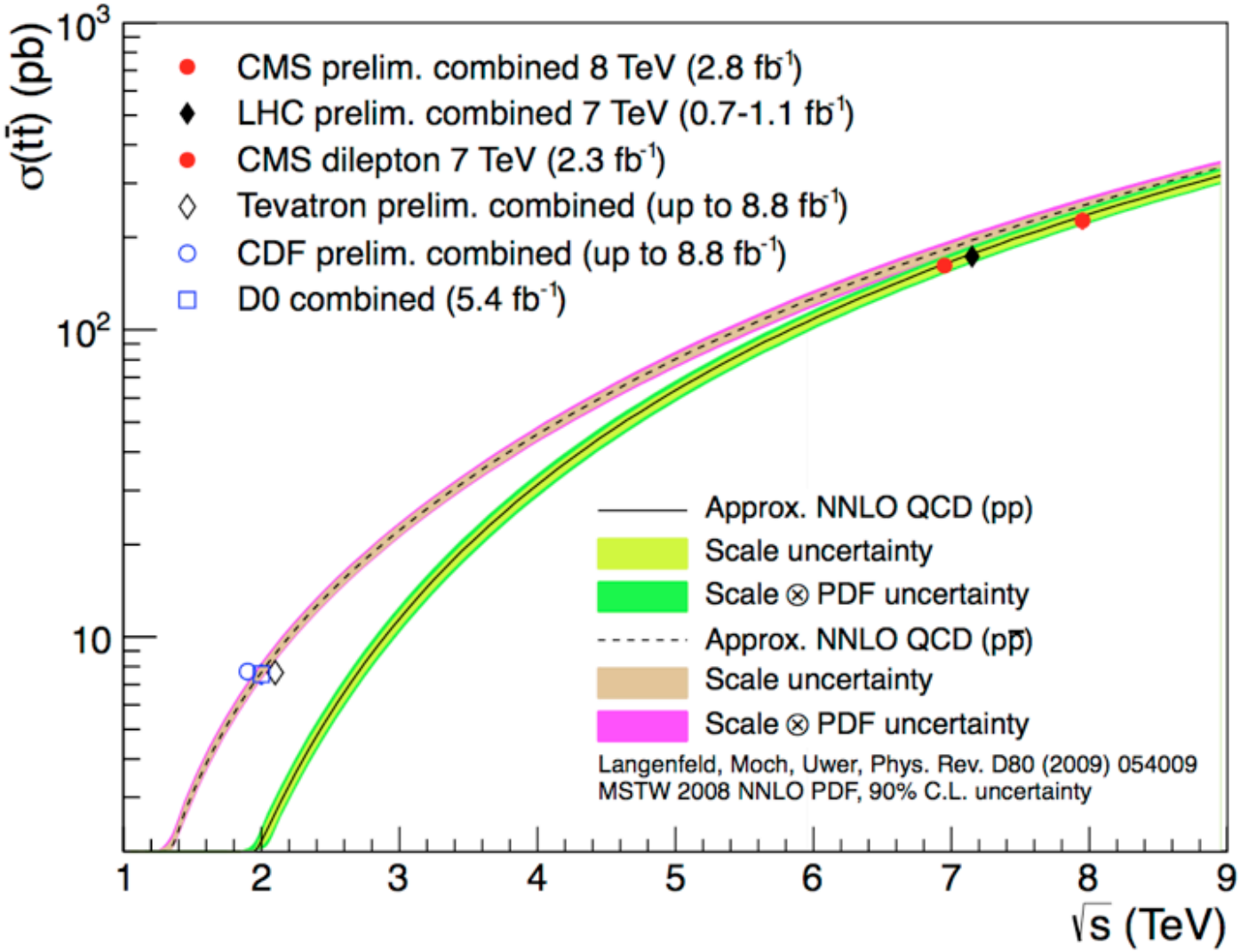
Top Pair Production Cross Section

May 2013



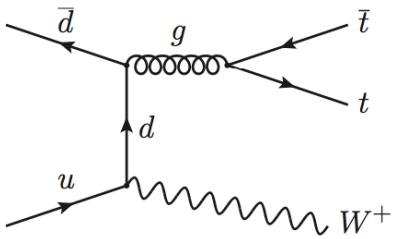
±5.4%

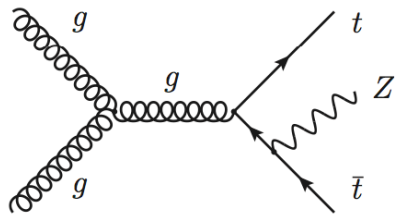
Top Pair Production Cross Section



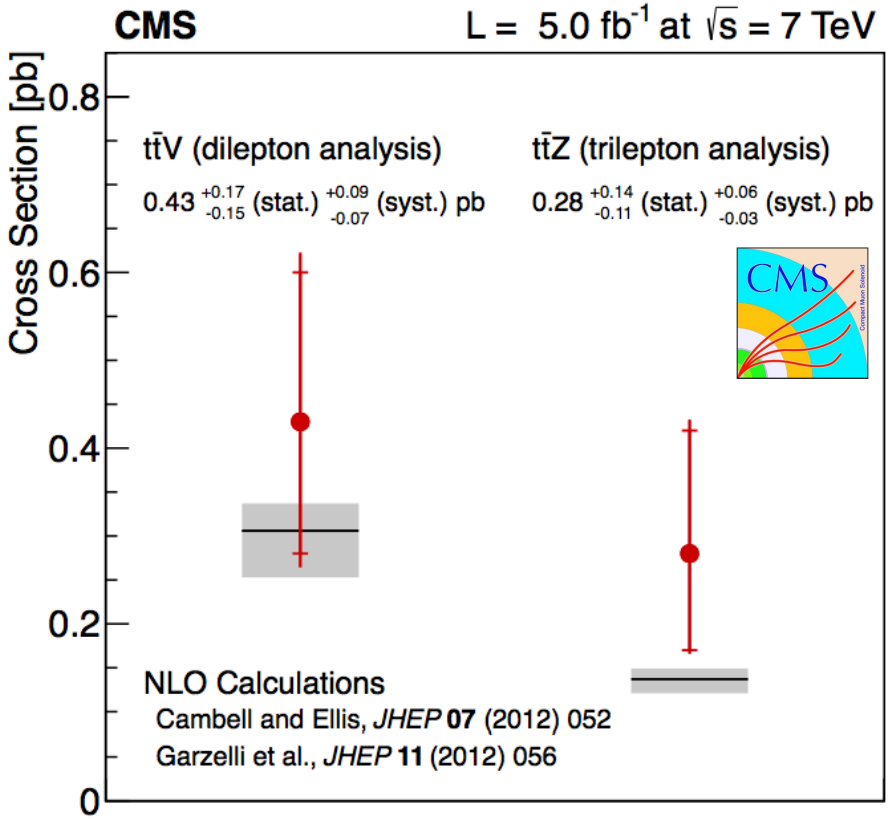
⇒ **good agreement with SM**

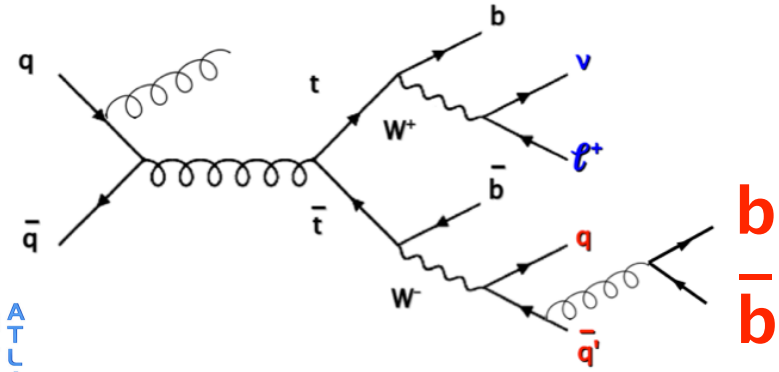
Top Pair Associated Production



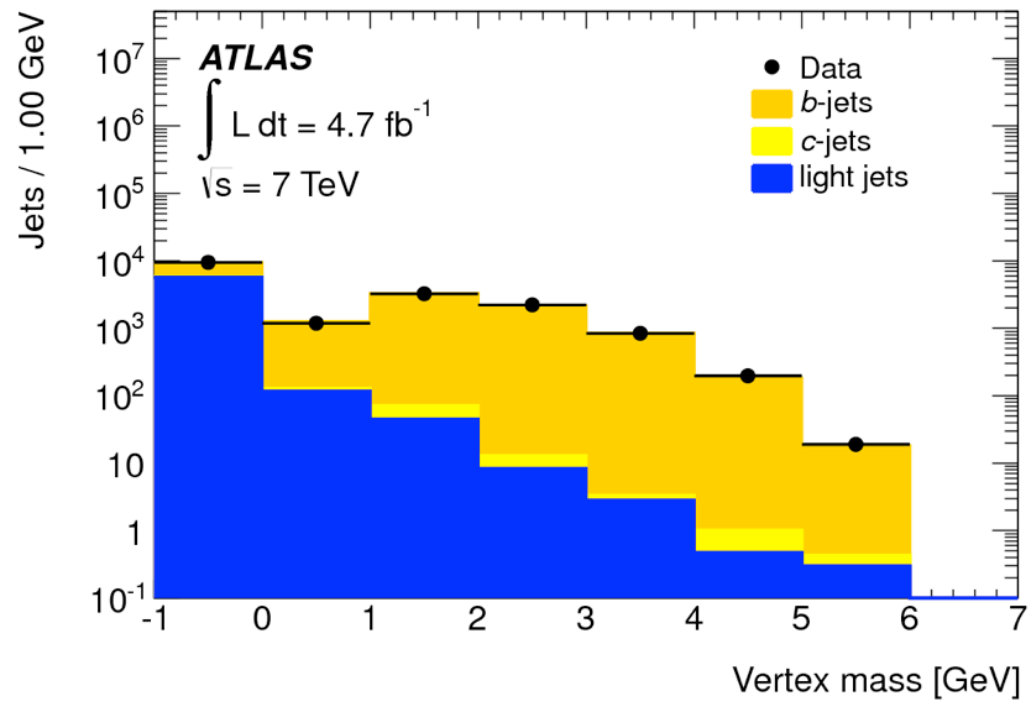


arXiv:1303.3239





arXiv:1304.6386



→ good agreement with higher order QCD calculations

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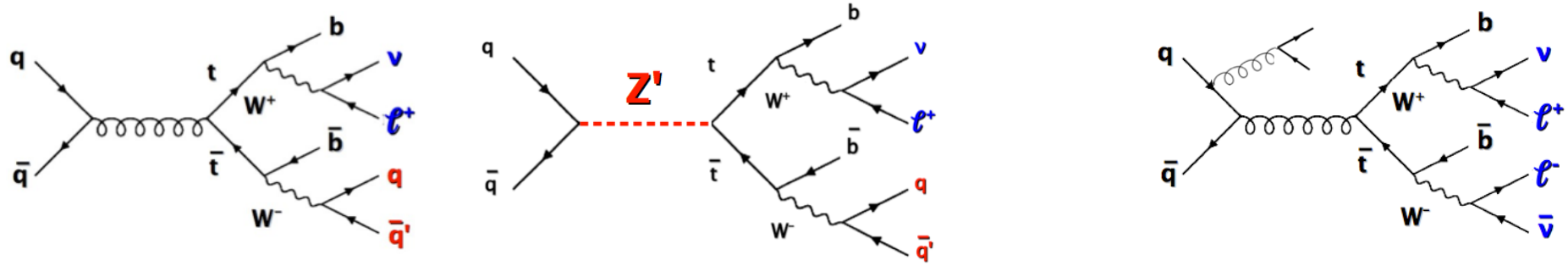
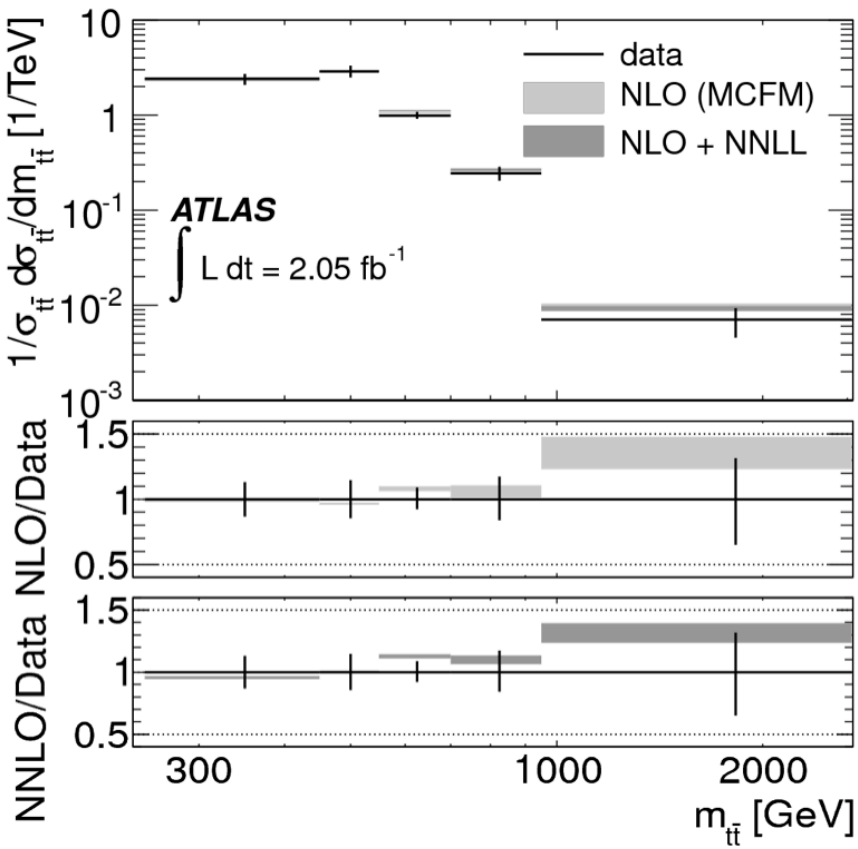
Differential Cross Sections

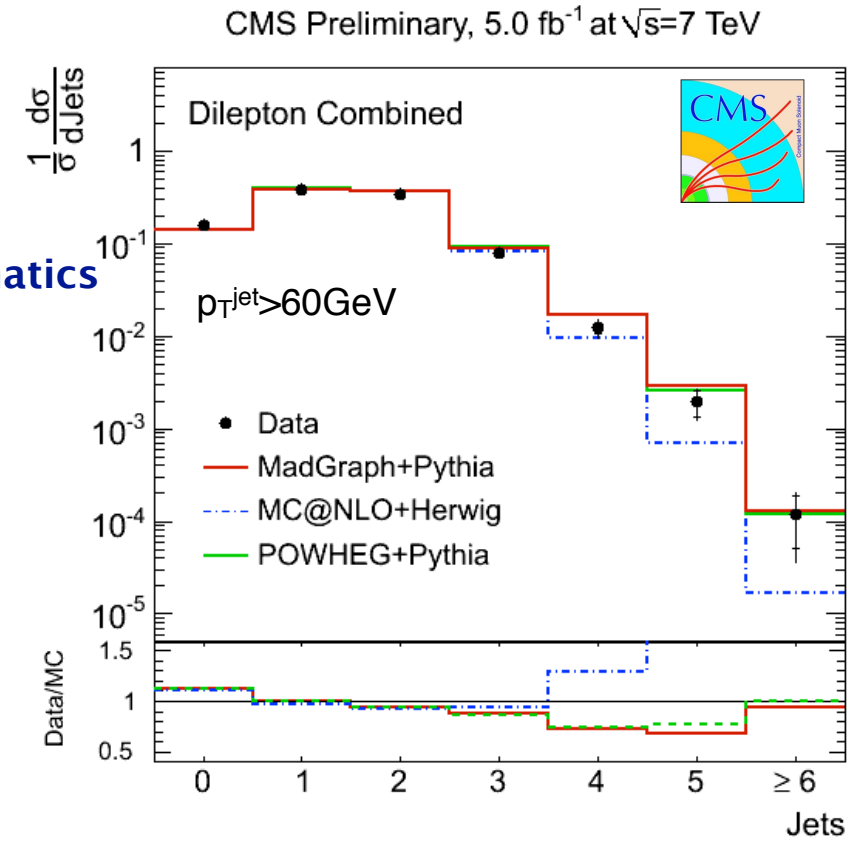


Eur. Phys. J. C 73, 2261 (2013)

CMS PAS TOP-12-023

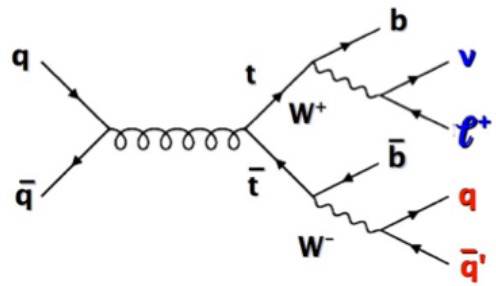


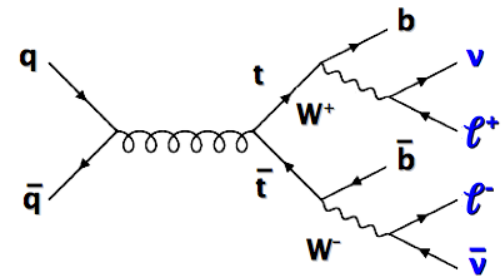
- **systematics limited**

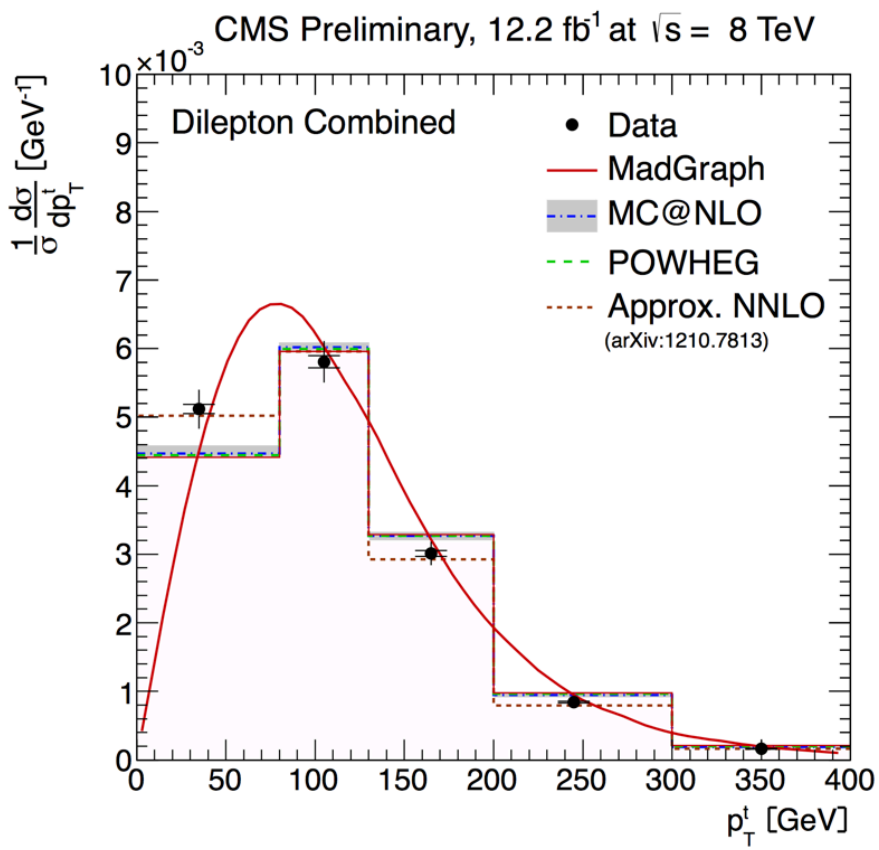


→ we are challenging NLO QCD calculations

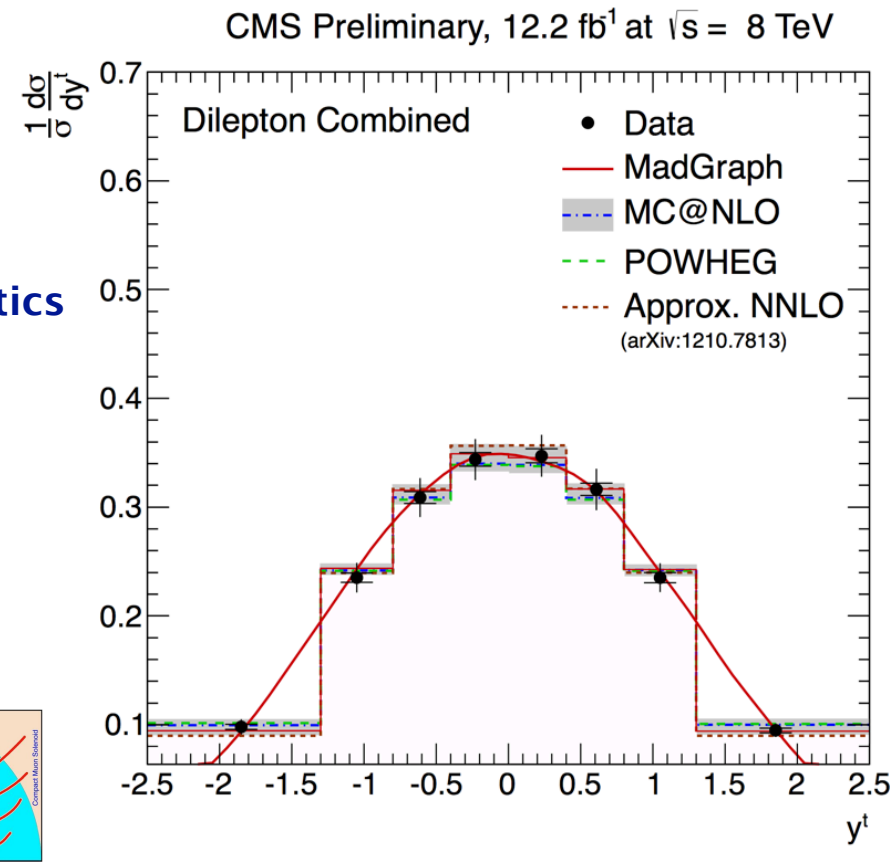
Differential Cross Sections







- systematics limited



→ we are challenging NLO QCD calculations

CMS-PAS-TOP-12-028

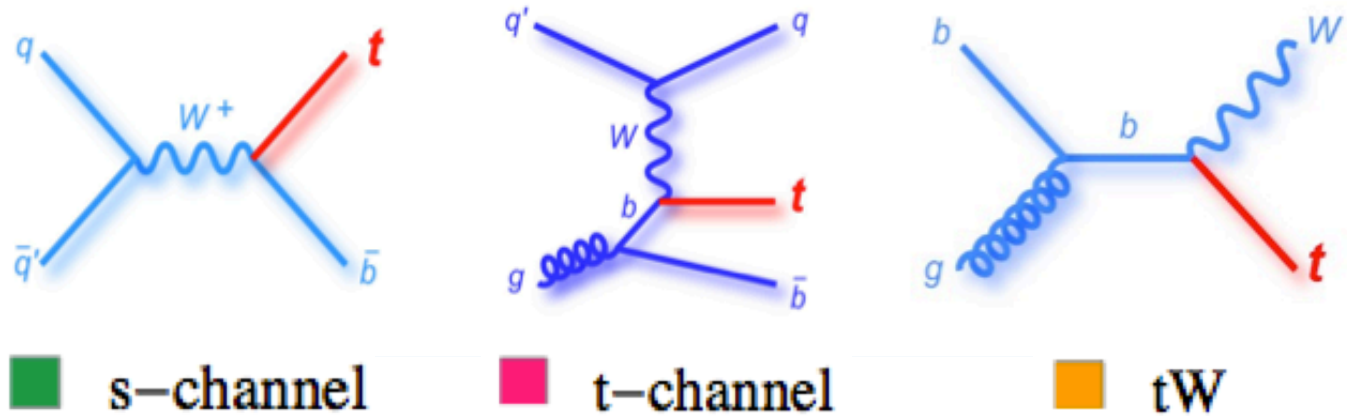
Outline

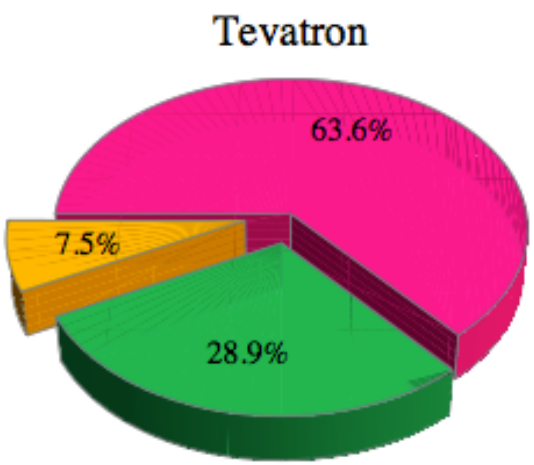
Introduction
Top Pair Production
Differential Cross Sections
Single Top Production
Top Pair Asymmetries
Conclusions

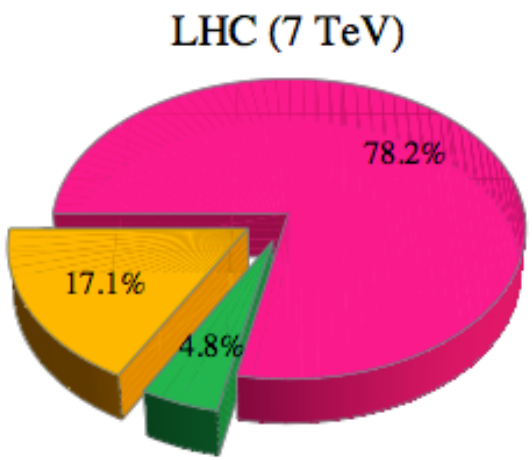
Single Top Quark Production

direct measurement of $|V_{tb}|$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

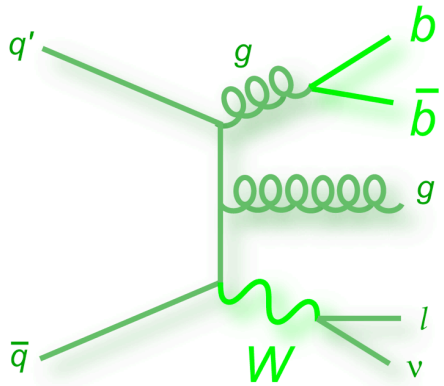


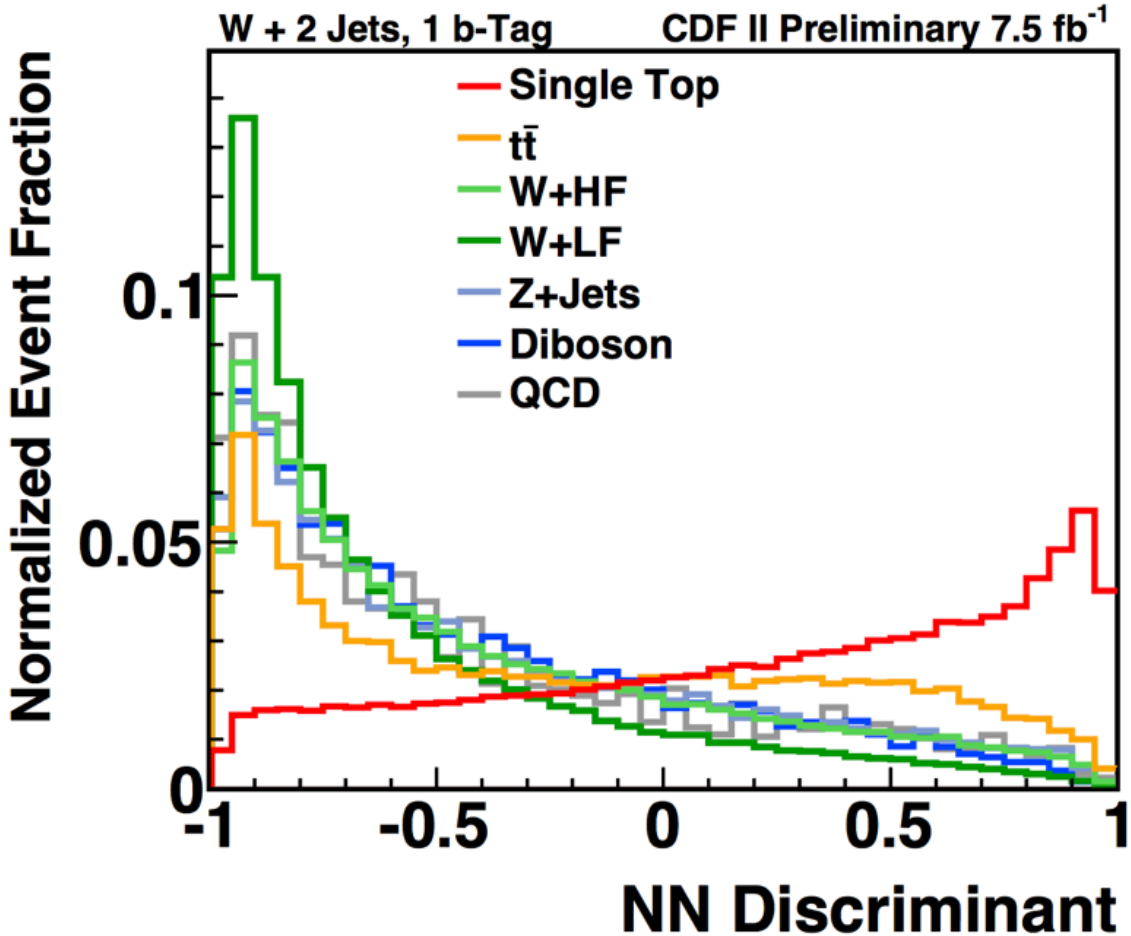


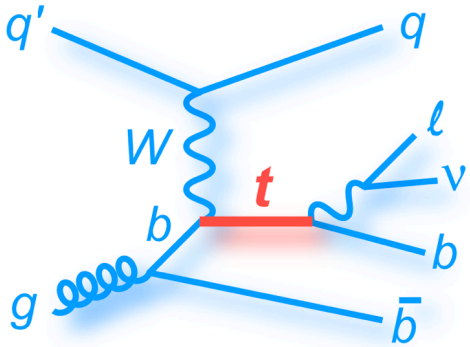


Output Discriminant for l+jets

CDF-CONF 10793

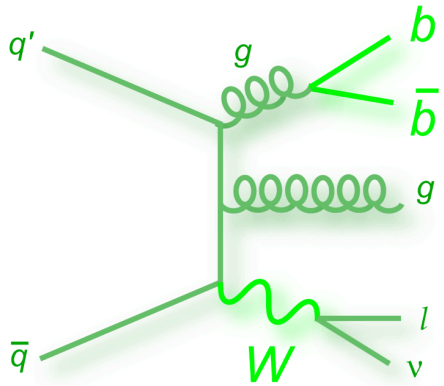


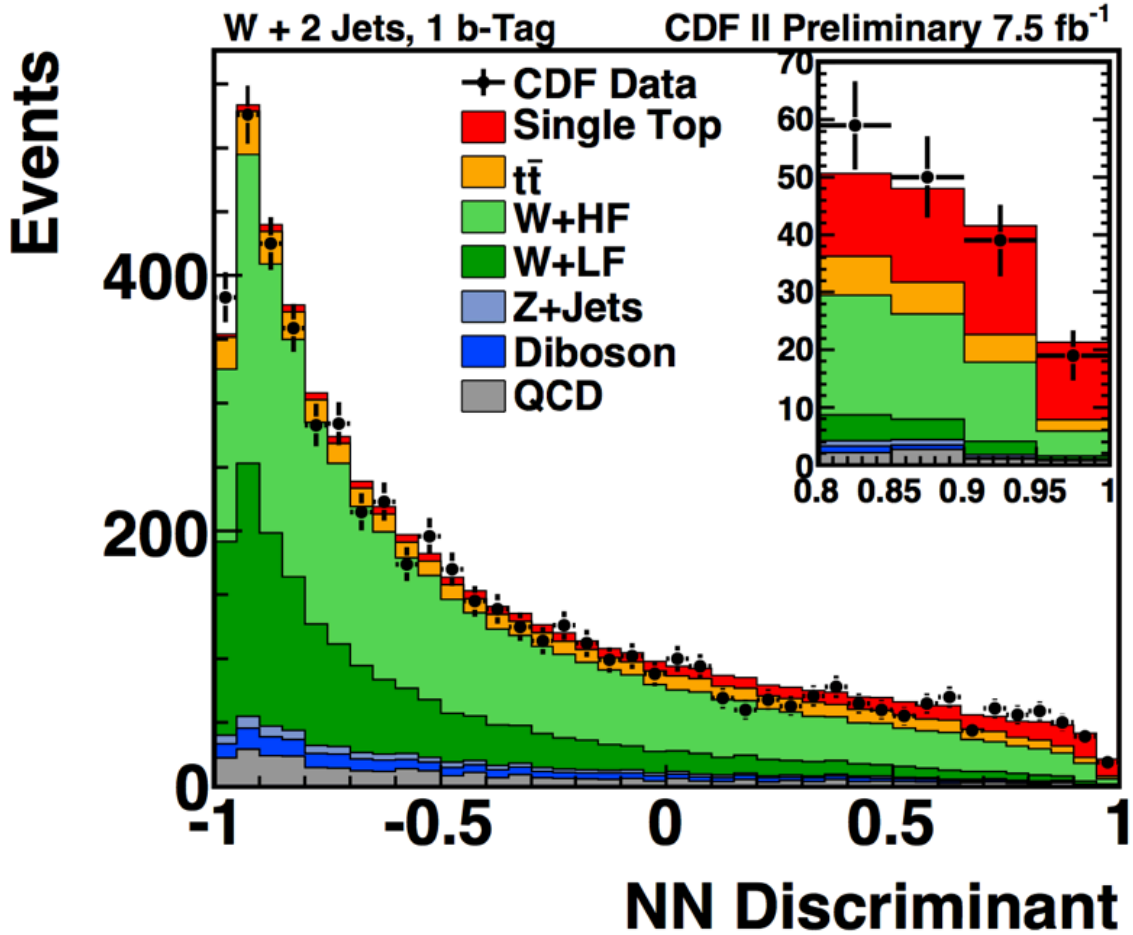


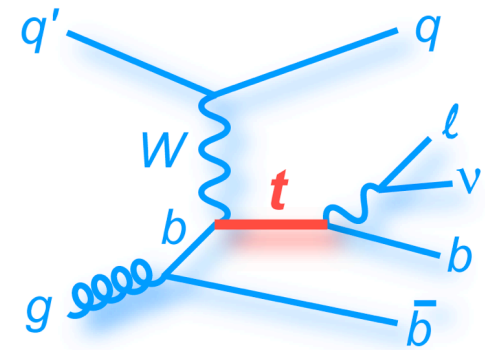


Output Discriminant for l+jets

CDF-CONF 10793



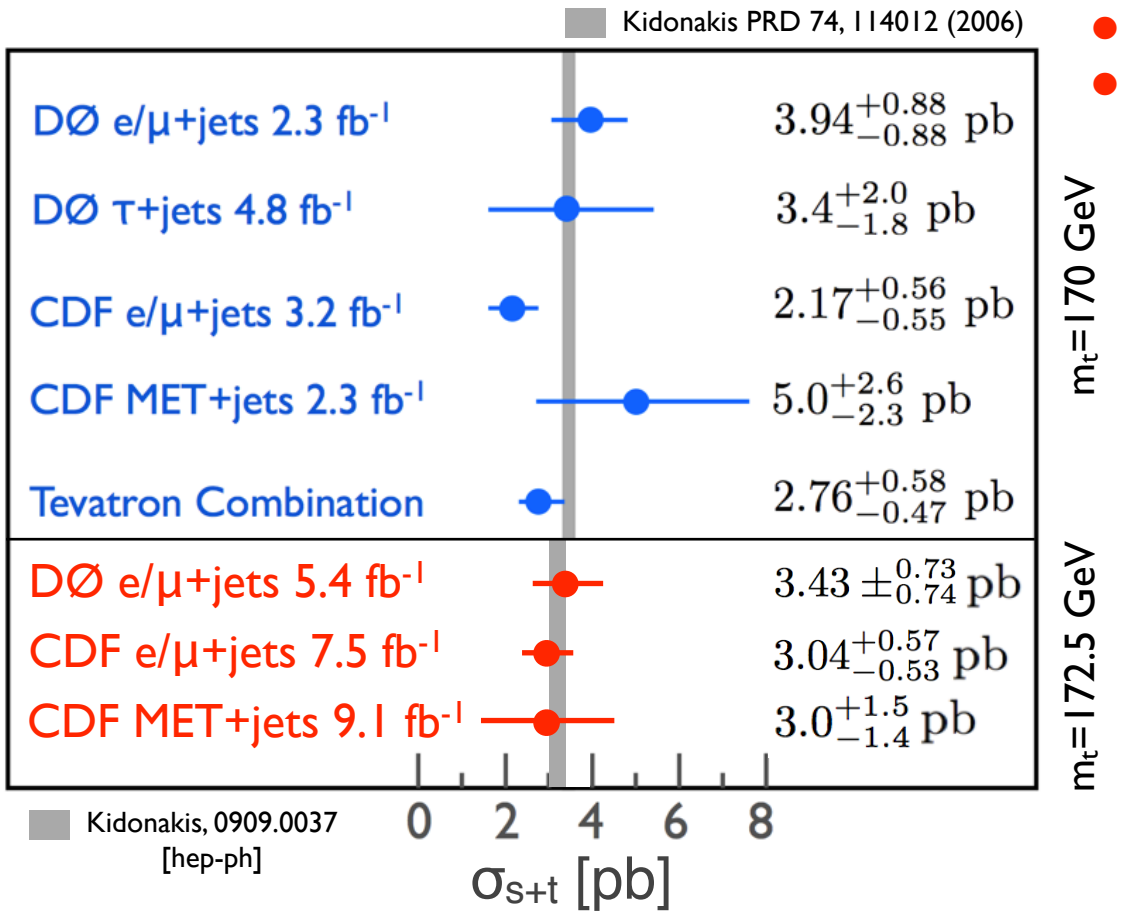




$$\sigma_{st} = 3.04^{+0.57}_{-0.53}\ \text{pb}$$

±18%

Single Top Production at the Tevatron



main Systematics:

- b-tagging
- W+jets normalisation
- jet energy scale/resolution

⇒ first observation by CDF and DØ

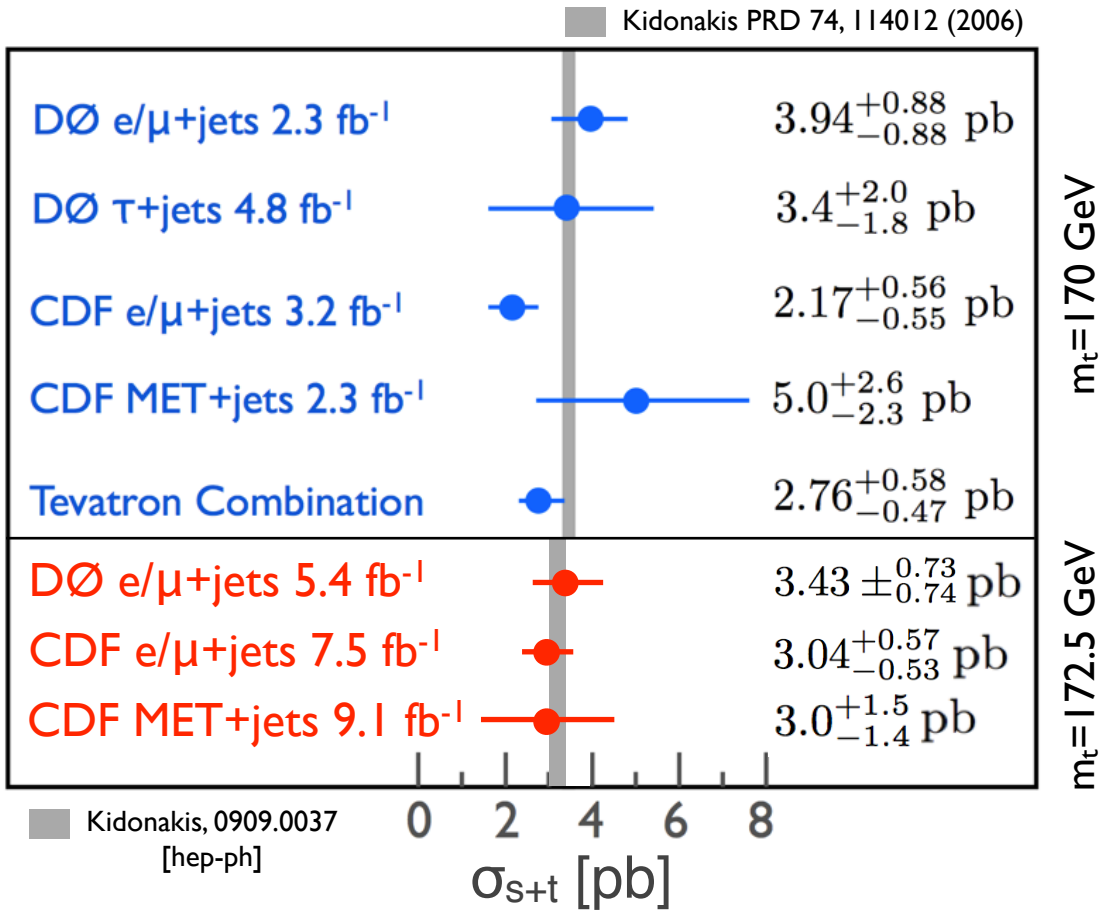
PRL 103, 092002 (2009)
PRL 103, 092001 (2009)

PRD 84 , 112001 (2011)
CDF-CONF 10793
CDF-CONF 10979

±18%

⇒ good agreement with Standard Model

Extraction of V_{tb}



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

arXiv:/0908.2171 [hep-ex]

$|V_{tb}| = 0.88 \pm 0.07$ $\pm 8\%$

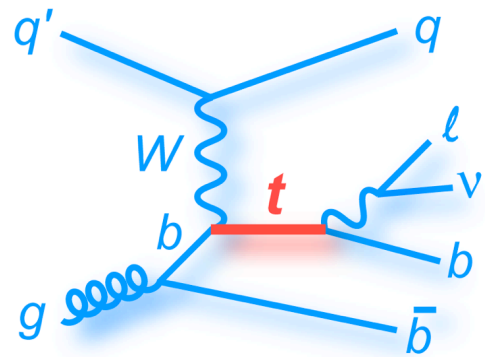
$|V_{tb}| = 0.92^{+0.10}_{-0.11}$

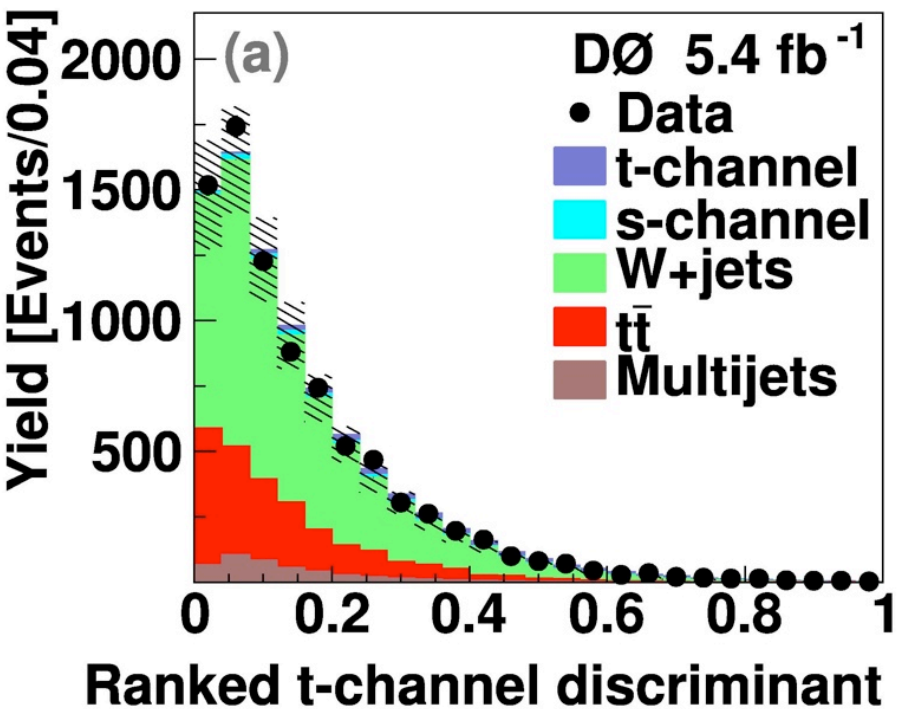
$|V_{tb}| = 0.92 \pm 0.10$

⇒ good agreement with Standard Model

Single Top t-channel Production

- remove s/t channel constraint which could be changed by new physics
- train multivariate analysis for t-channel
- measure s- and t-channel simultaneously



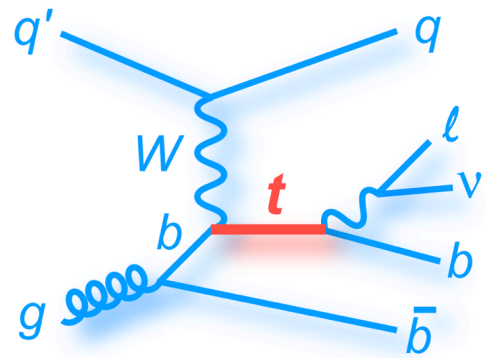


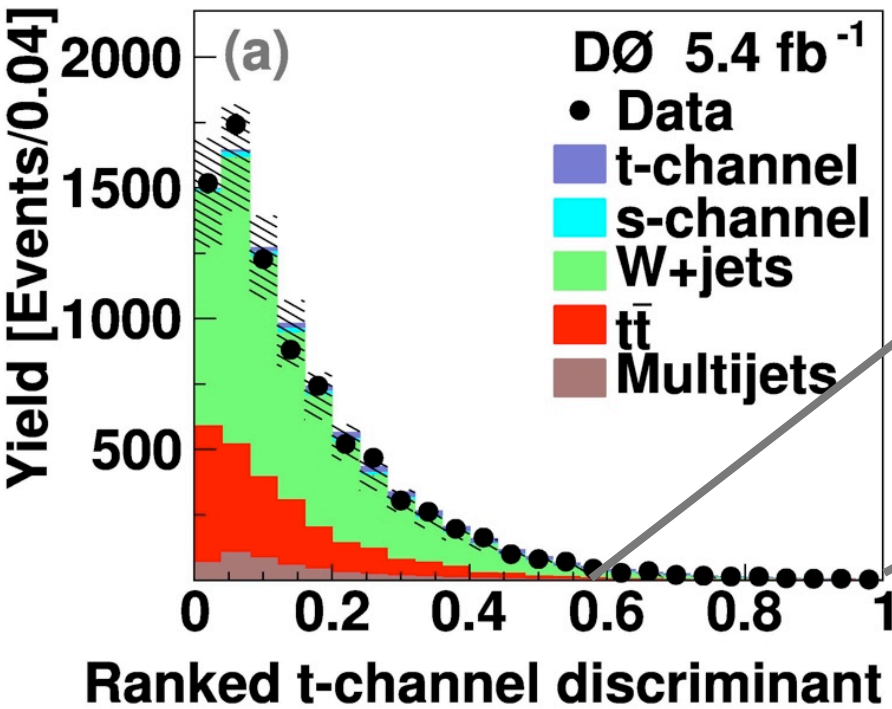
PLB 705, 313 (2011)

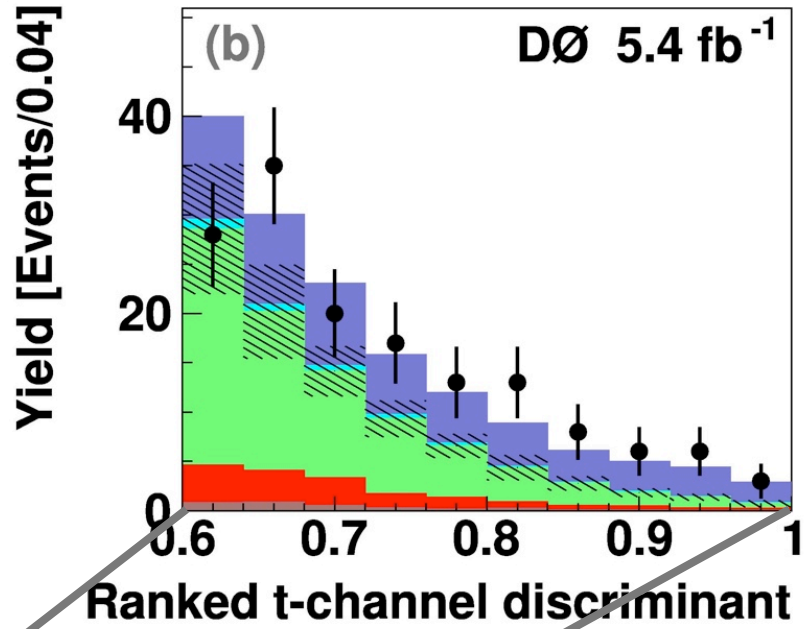
first observation with 5.5σ

Single Top t-channel Production

- remove s/t channel constraint which could be changed by new physics
- train multivariate analysis for t-channel
- measure s- and t-channel simultaneously







PLB 705, 313 (2011)

first observation with 5.5σ

Single Top t-channel Production

- remove s/t channel constraint which could be changed by new physics
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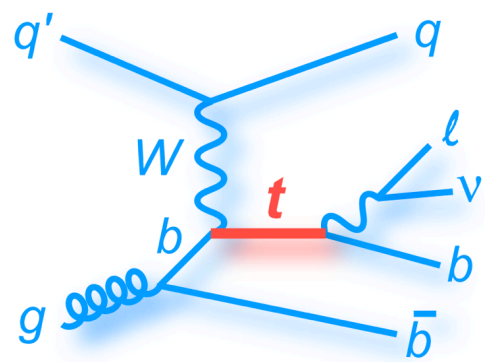
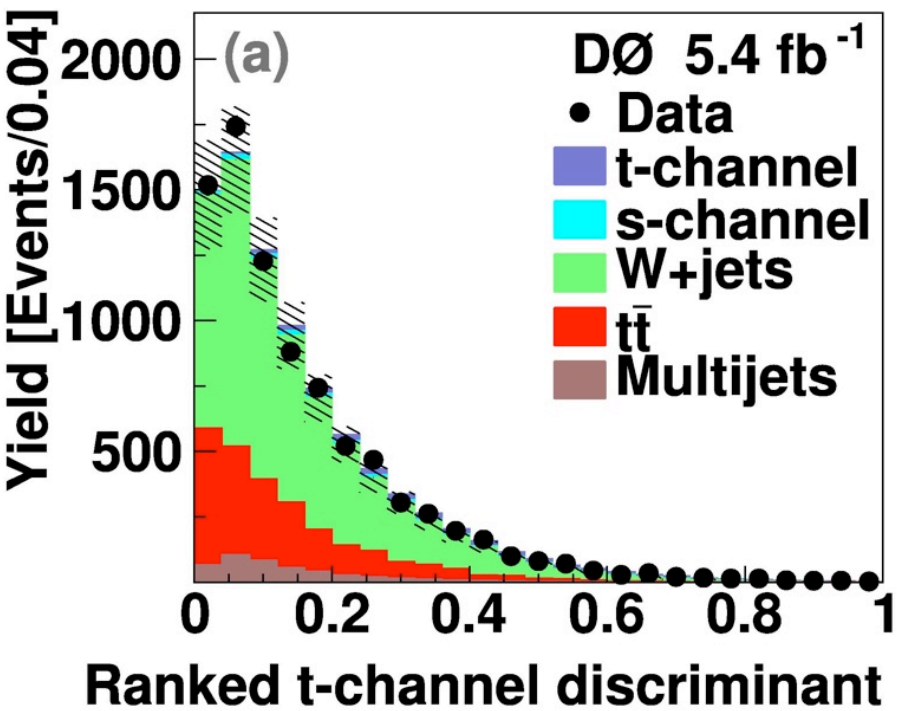


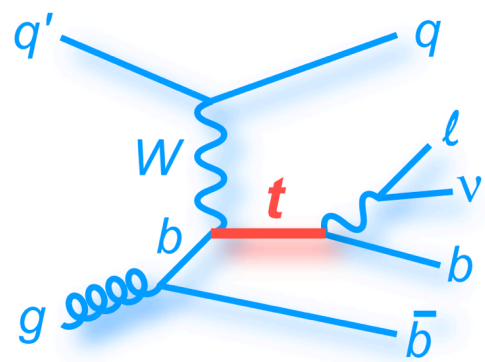


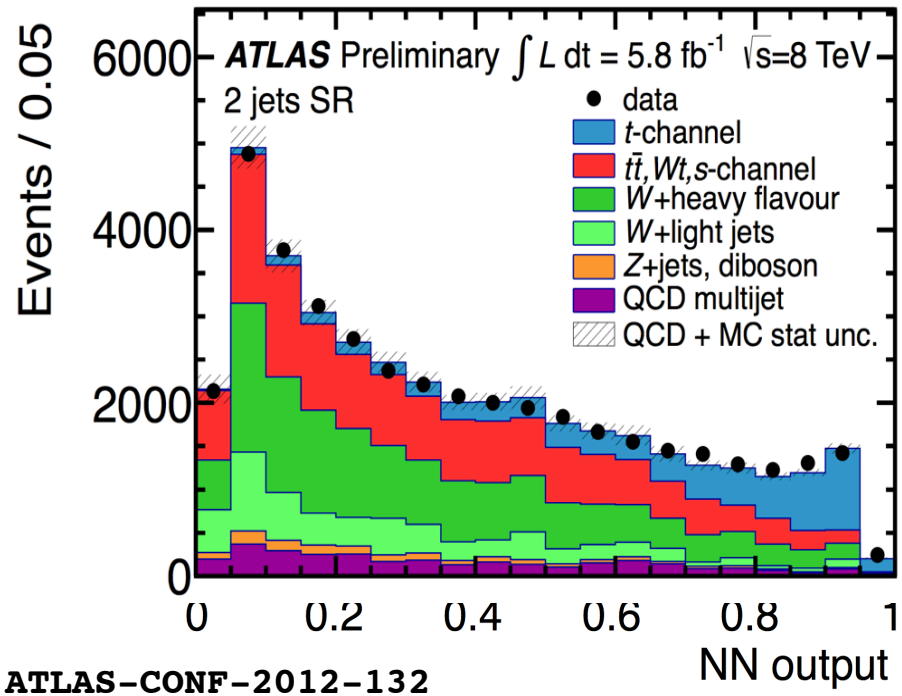
PLB 705, 313 (2011)

first observation with 5.5σ

Single Top t-channel Production

- remove s/t channel constraint which could be changed by new physics
- train multivariate analysis for t-channel



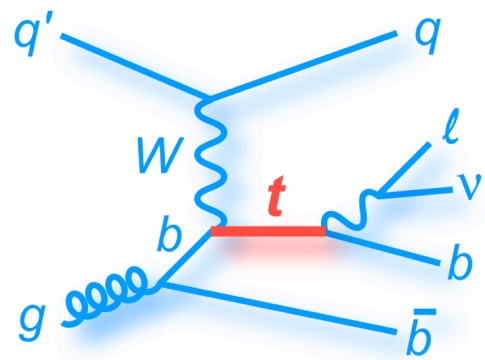


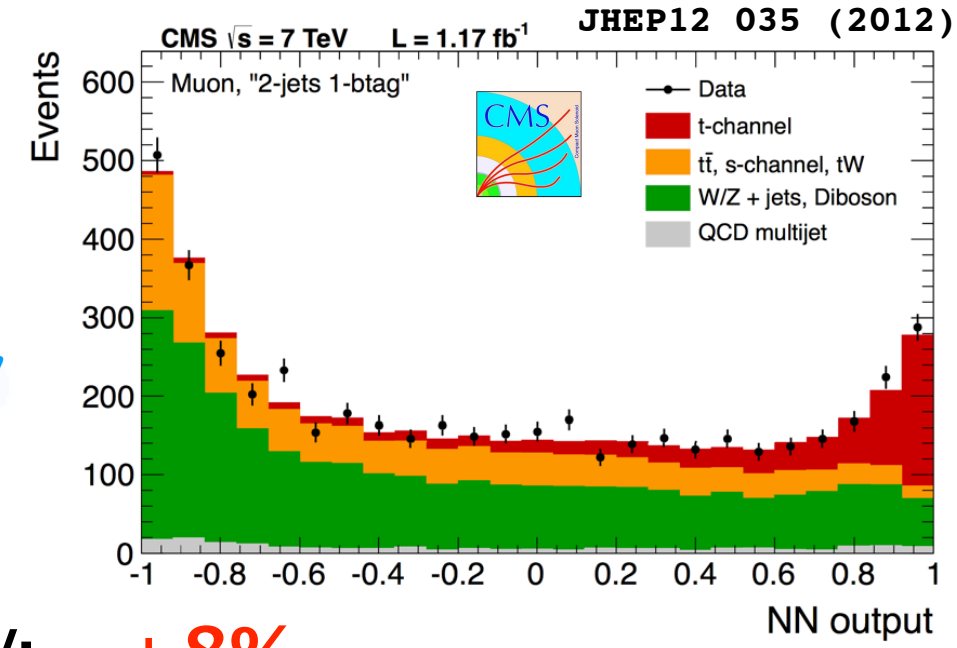
ATLAS-CONF-2012-132

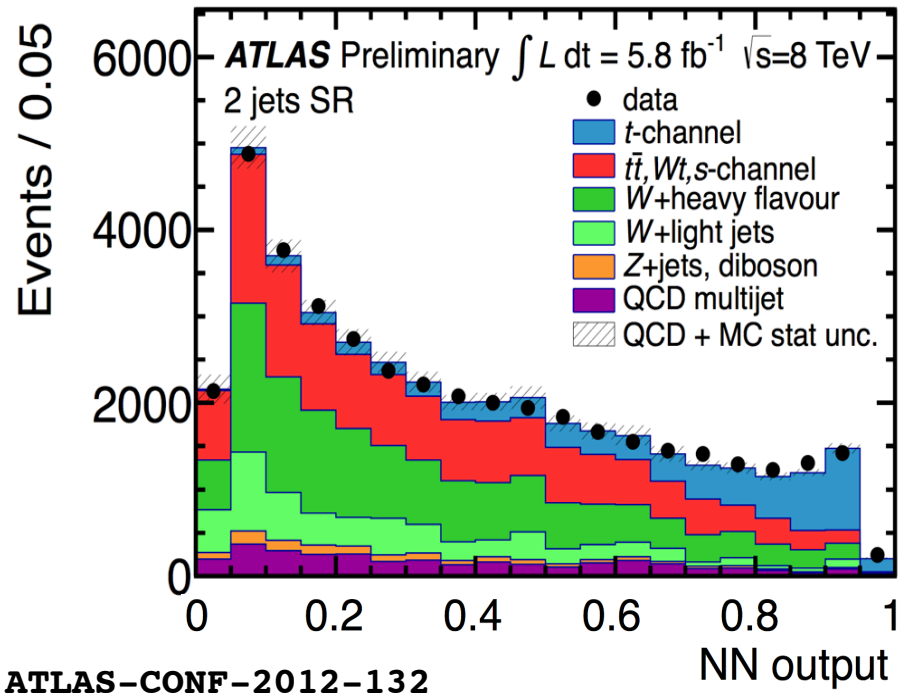
Single Top t-channel Production

main Systematics:

- t-channel generator, ISR/FSR
- b-tagging







ATLAS-CONF-2012-132

7 TeV: ±8%

σ_t=67.2 ± 3.7 (stat) ± 3.5 (syst) ± 1.5 (lumi) pb

$|V_{tb}| = 1.04 \pm 0.049$ ±5%

8 TeV: ±19%

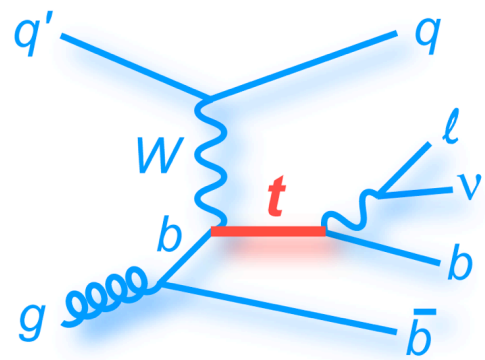
σ_t=95.1 ± 2.4 (stat) ± 18.0 (syst) pb

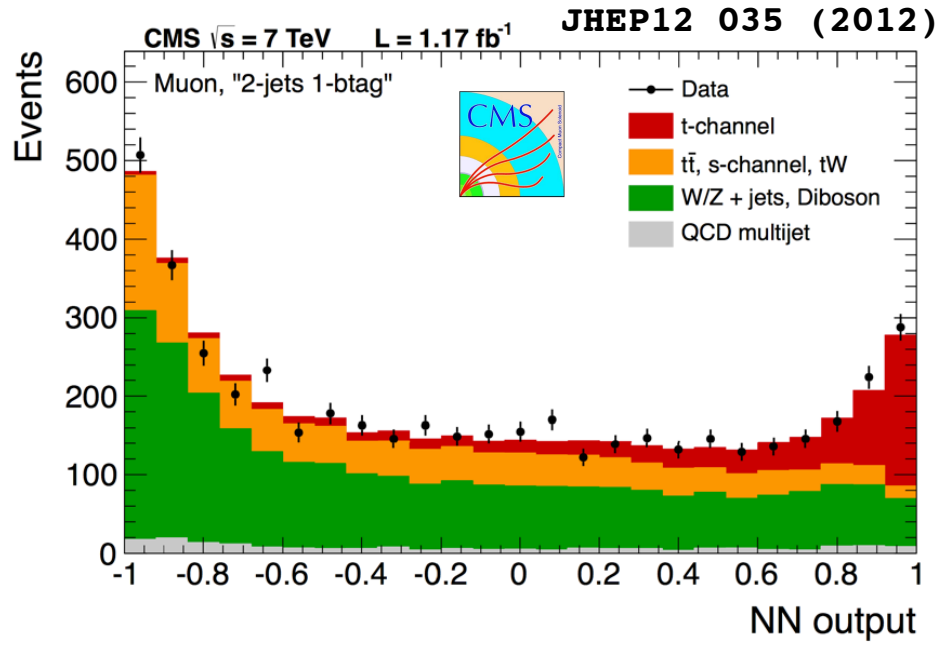
$|V_{tb}| = 1.04^{+0.10}_{-0.11}$ ±10%

Single Top t-channel Production

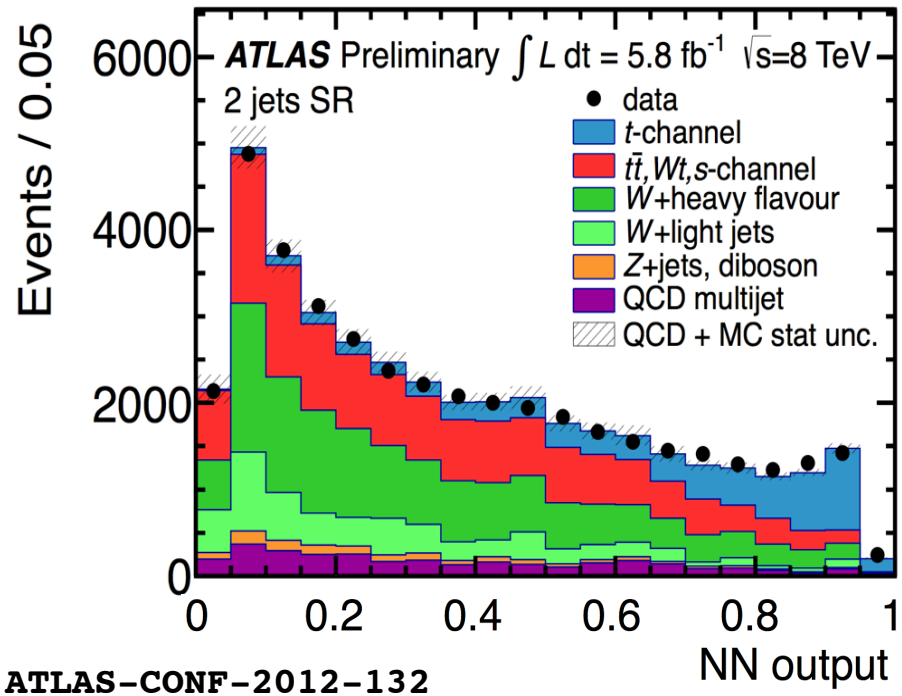
main Systematics:

- t-channel generator, ISR/FSR
- b-tagging



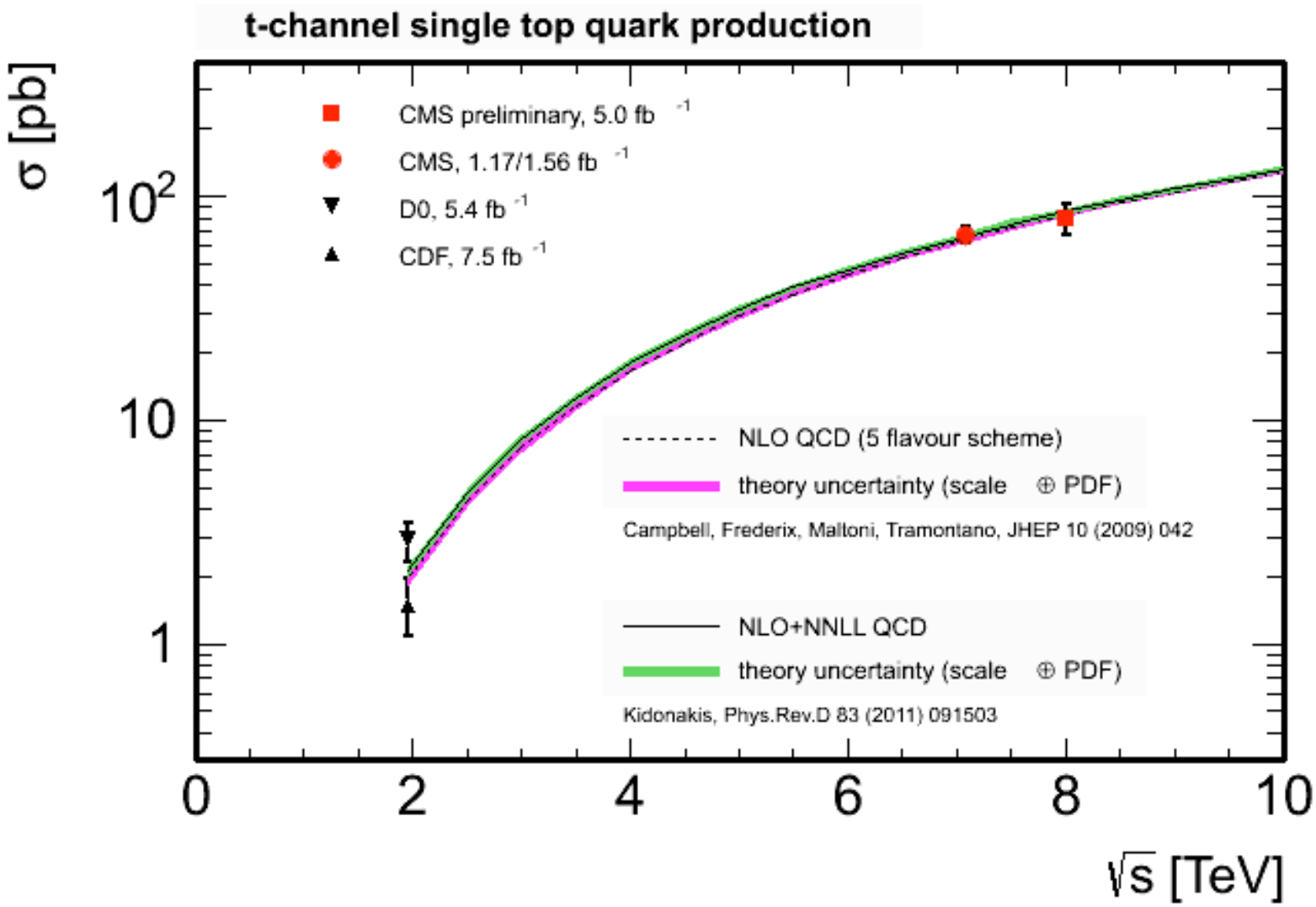


JHEP12 035 (2012)



ATLAS-CONF-2012-132

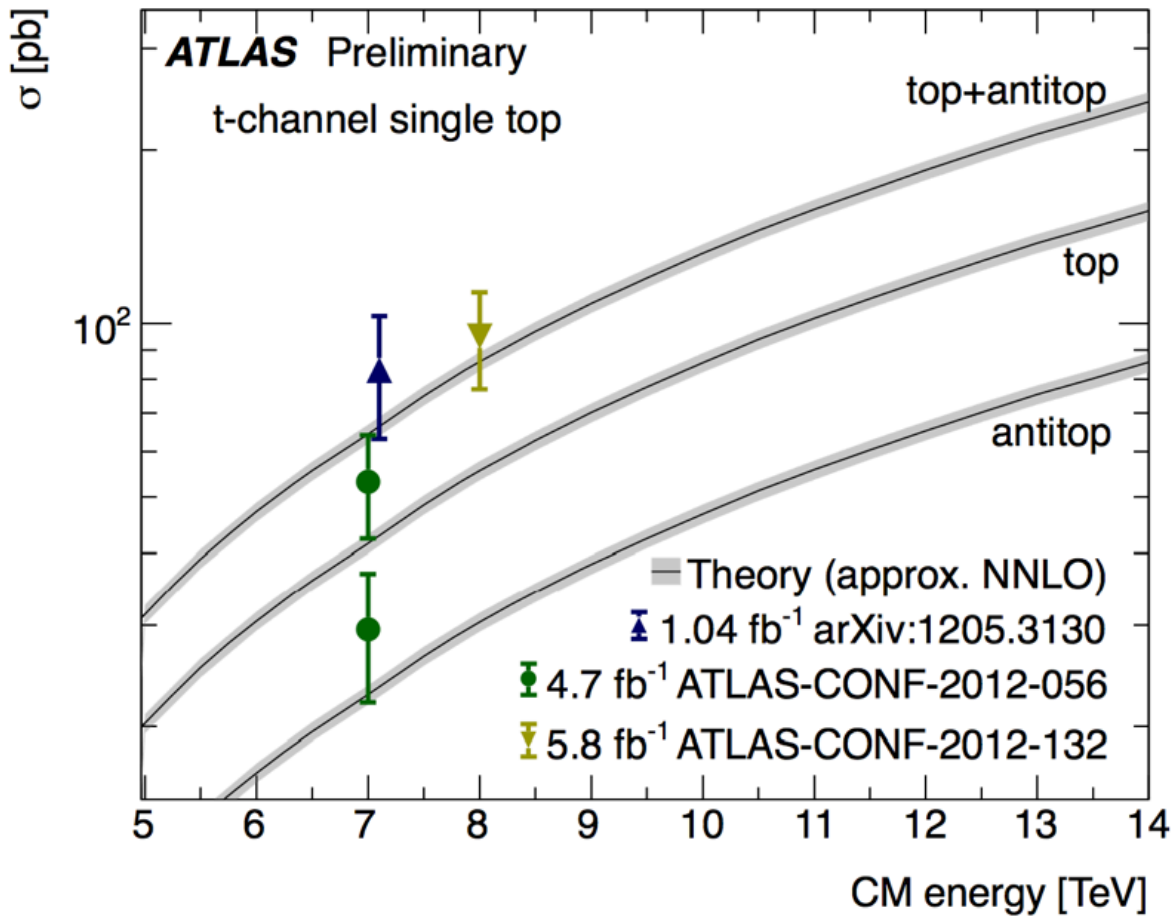
Single Top t-channel Production

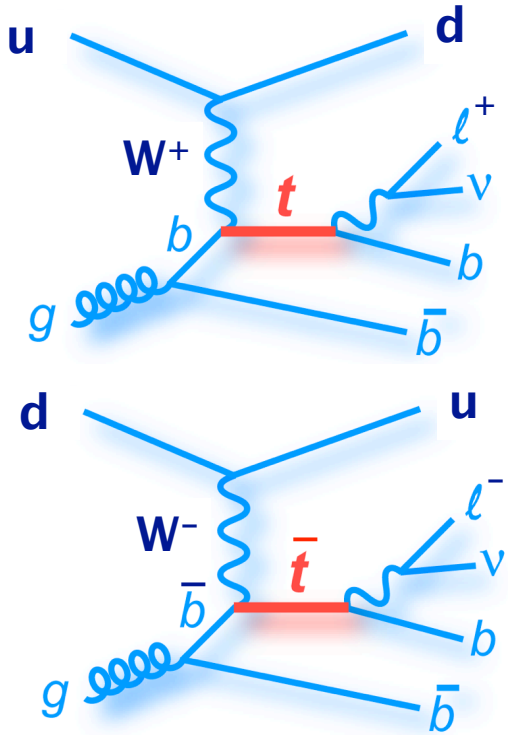


⇒ **good agreement with SM**

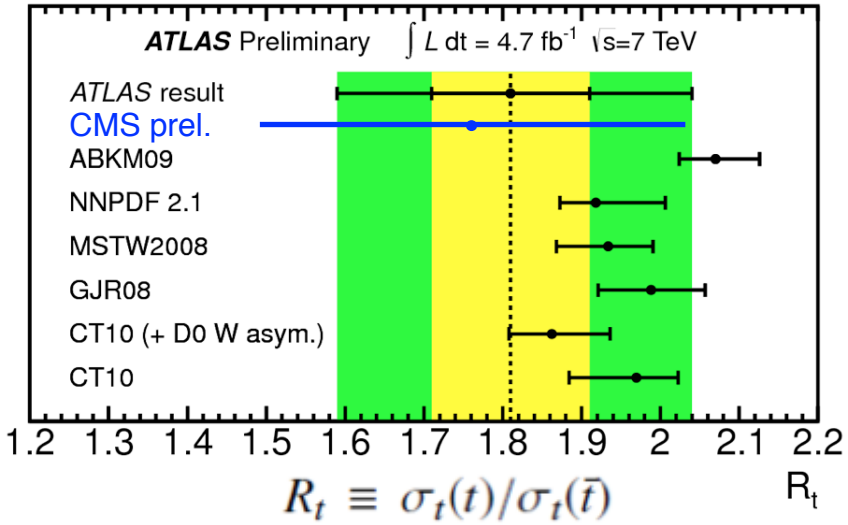
Single Top t-channel Production

ATLAS-CONF-2012-132





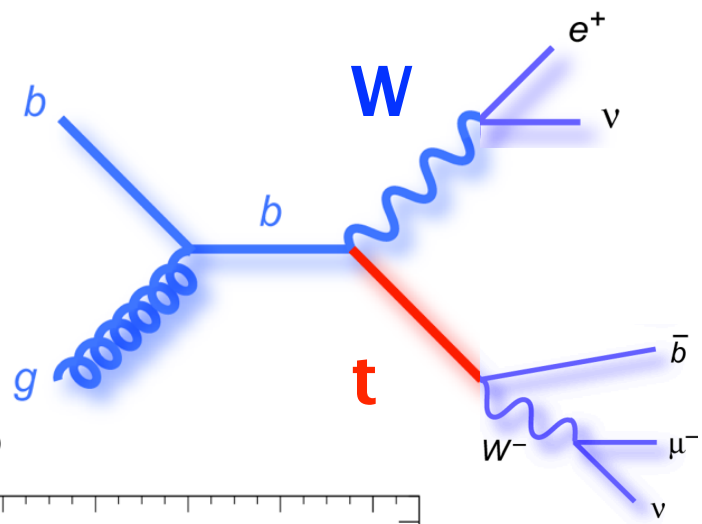
ATLAS-CONF-2012-056



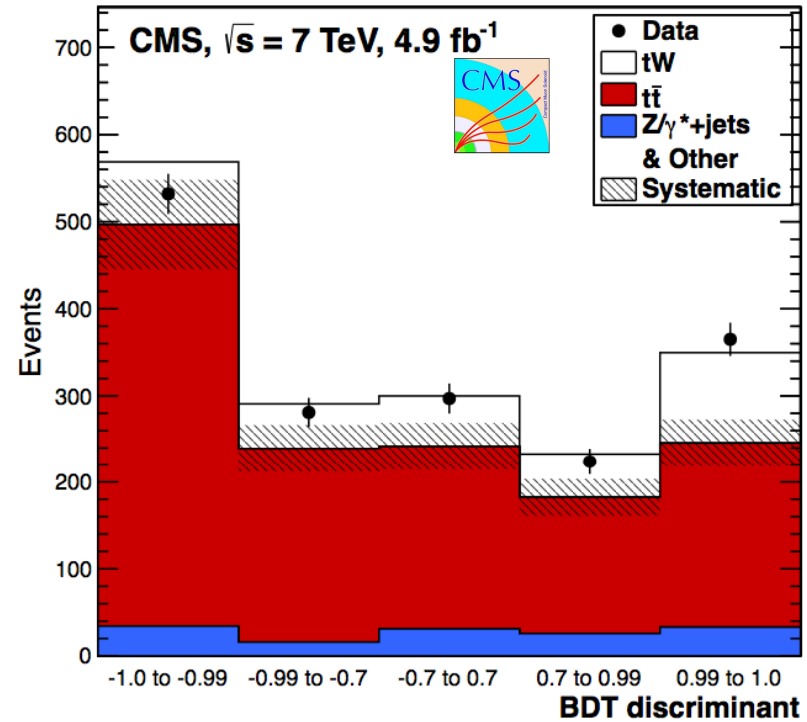
⇒ **good agreement with SM**

Wt-channel Production

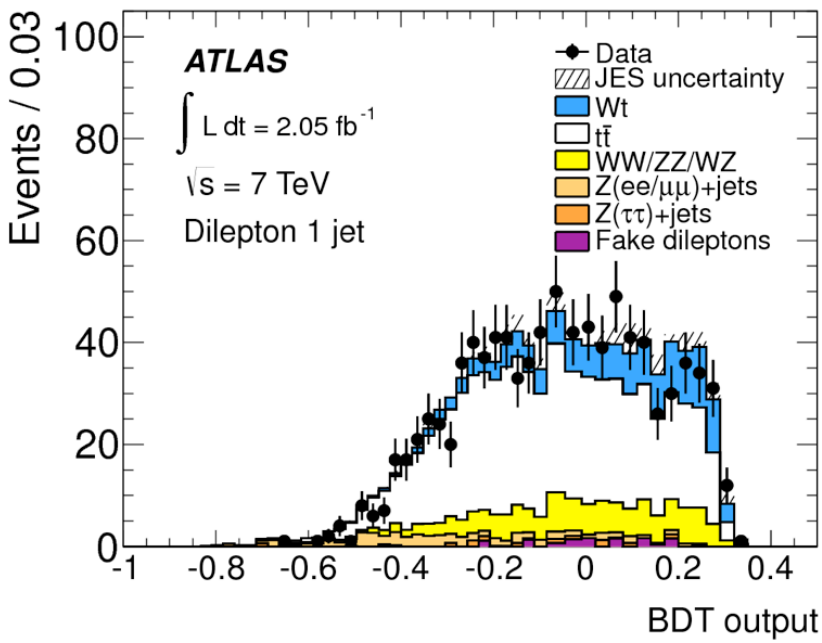
- train multivariate analysis for Wt-channel



PRL 110, 022003 (2013)



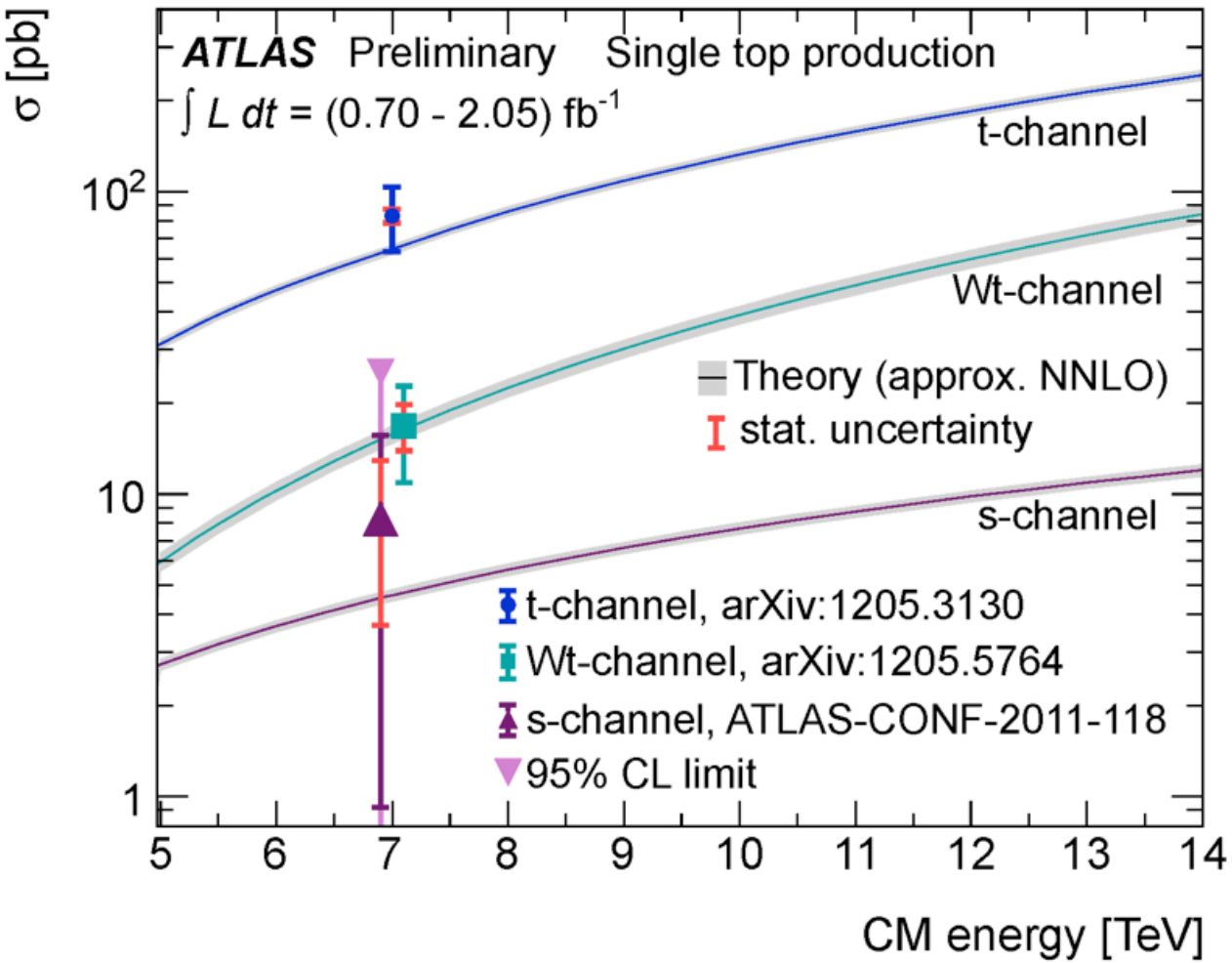
PLB 716, 142 (2012)

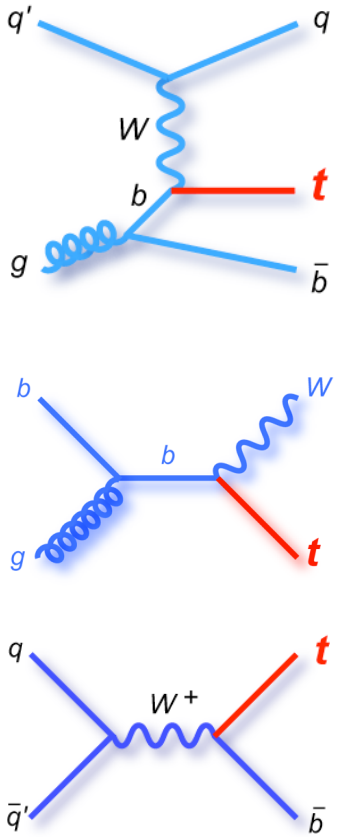


evidence with 4.0σ

evidence with 3.3σ

Single Production Channels at the LHC





⇒ good agreement with Standard Model

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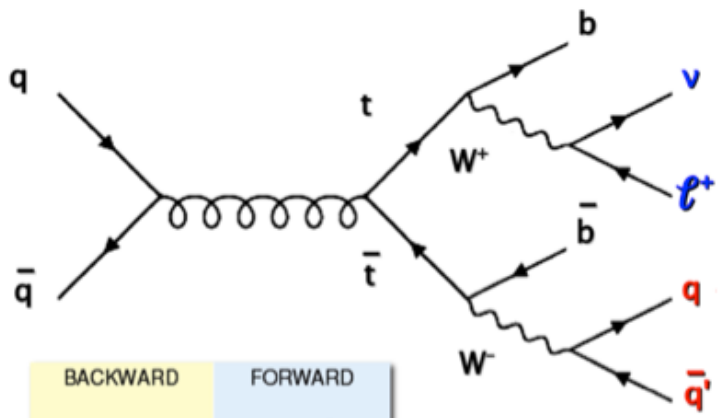
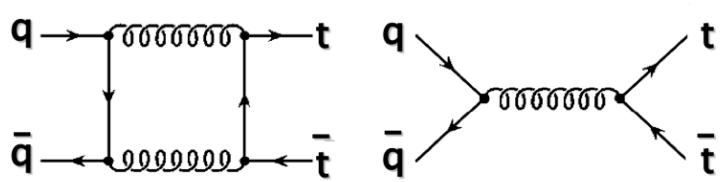
Forward Backward Charge Asymmetry



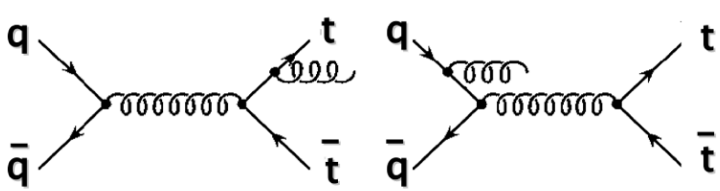
$$A_{fb} = \frac{F - B}{F + B}$$

- asymmetry in $O(\alpha_s^3)$ **NLO QCD**

interference between:



interference between:

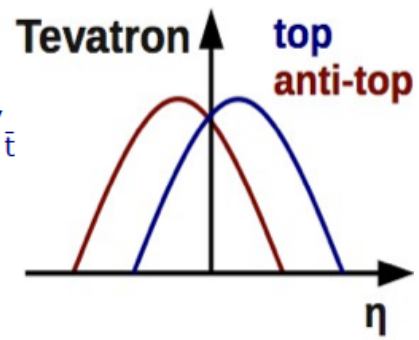


- **complementary between $p\bar{p}$ and pp**

Tevatron

$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

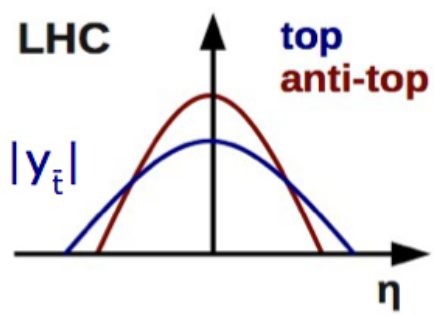
$\Delta y = y_t - y_{\bar{t}}$



LHC

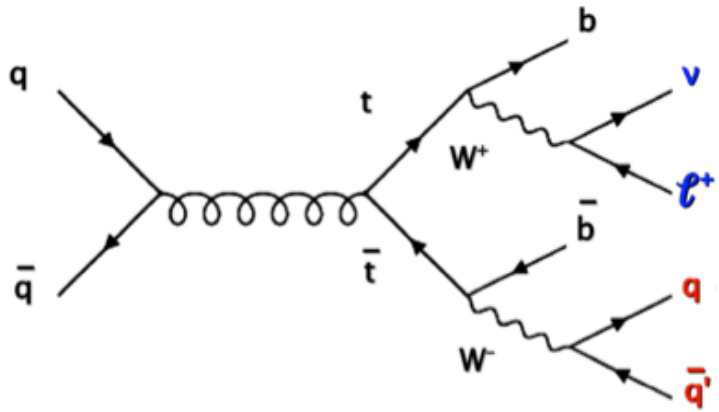
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

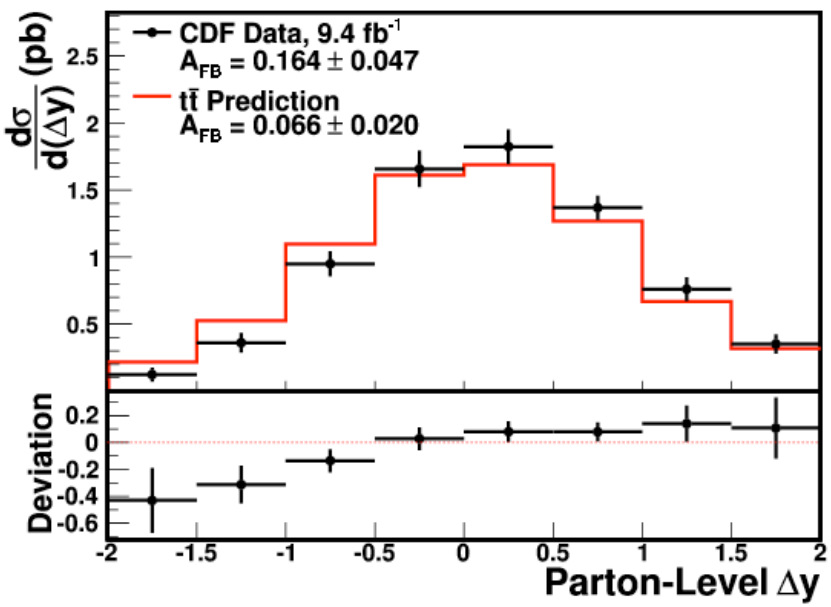
$\Delta|y| = |y_t| - |y_{\bar{t}}|$

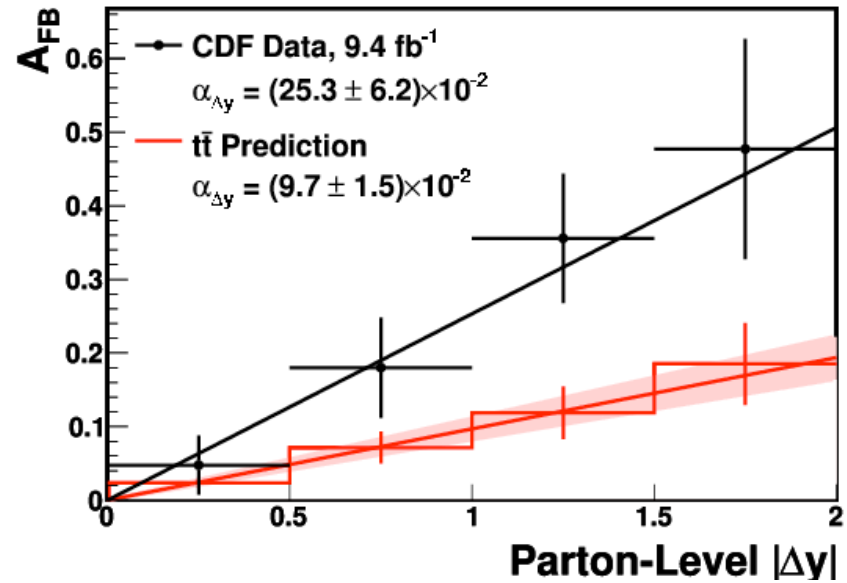


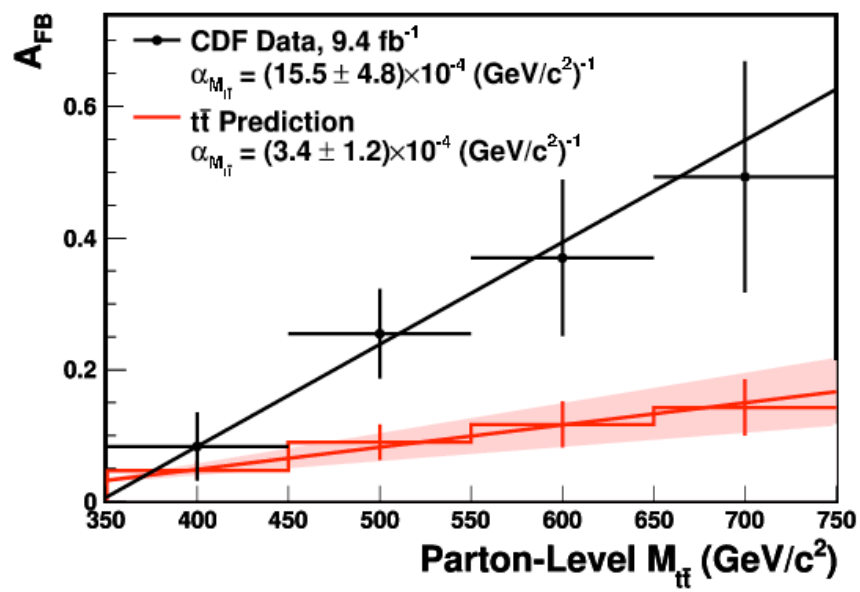
Forward Backward Charge Asymmetry

PRD 87, 092002 (2013)









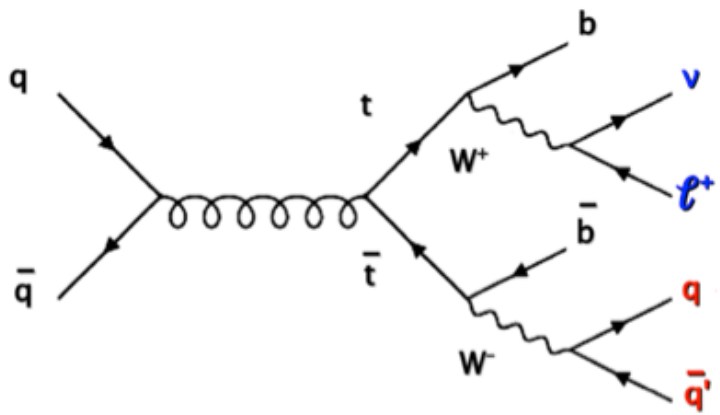
1.9σ

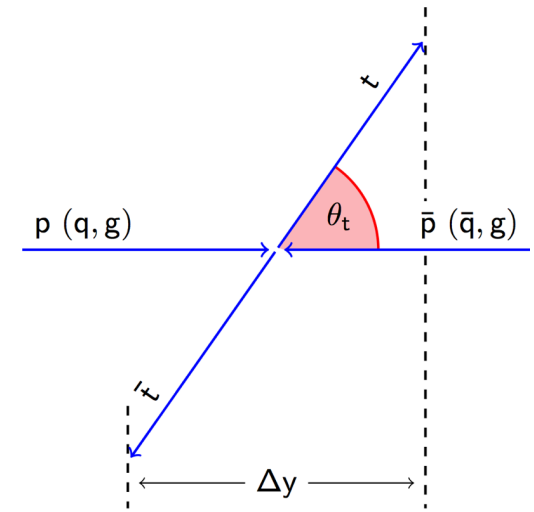
A_{fb} = 0.162 ± 0.047 (stat.+syst.)

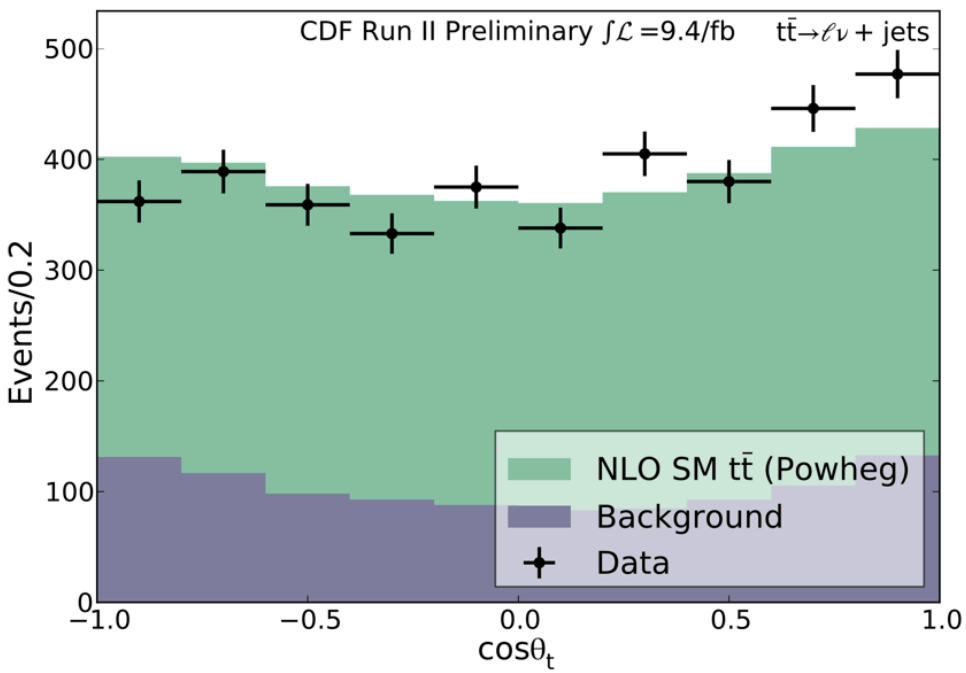
NLO QCD+EWK: A_{fb} = 0.066

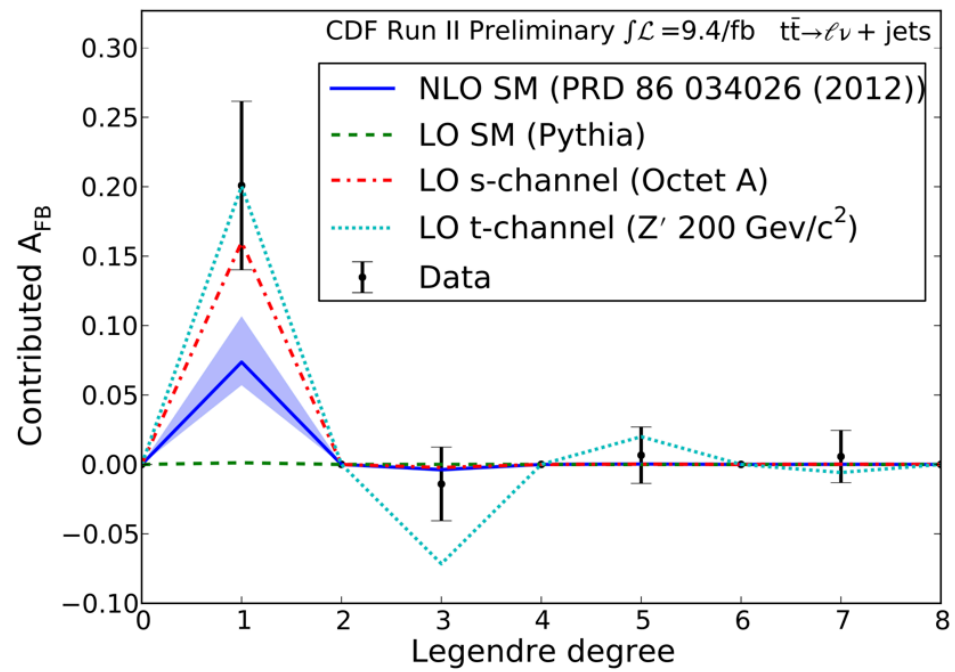
Angular Distribution

CDF-CONF 10974

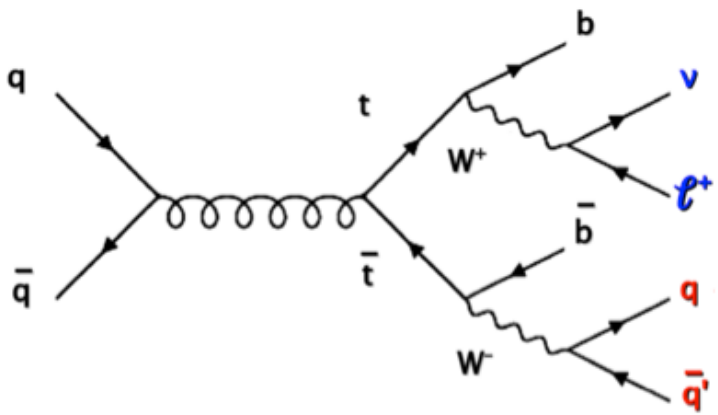


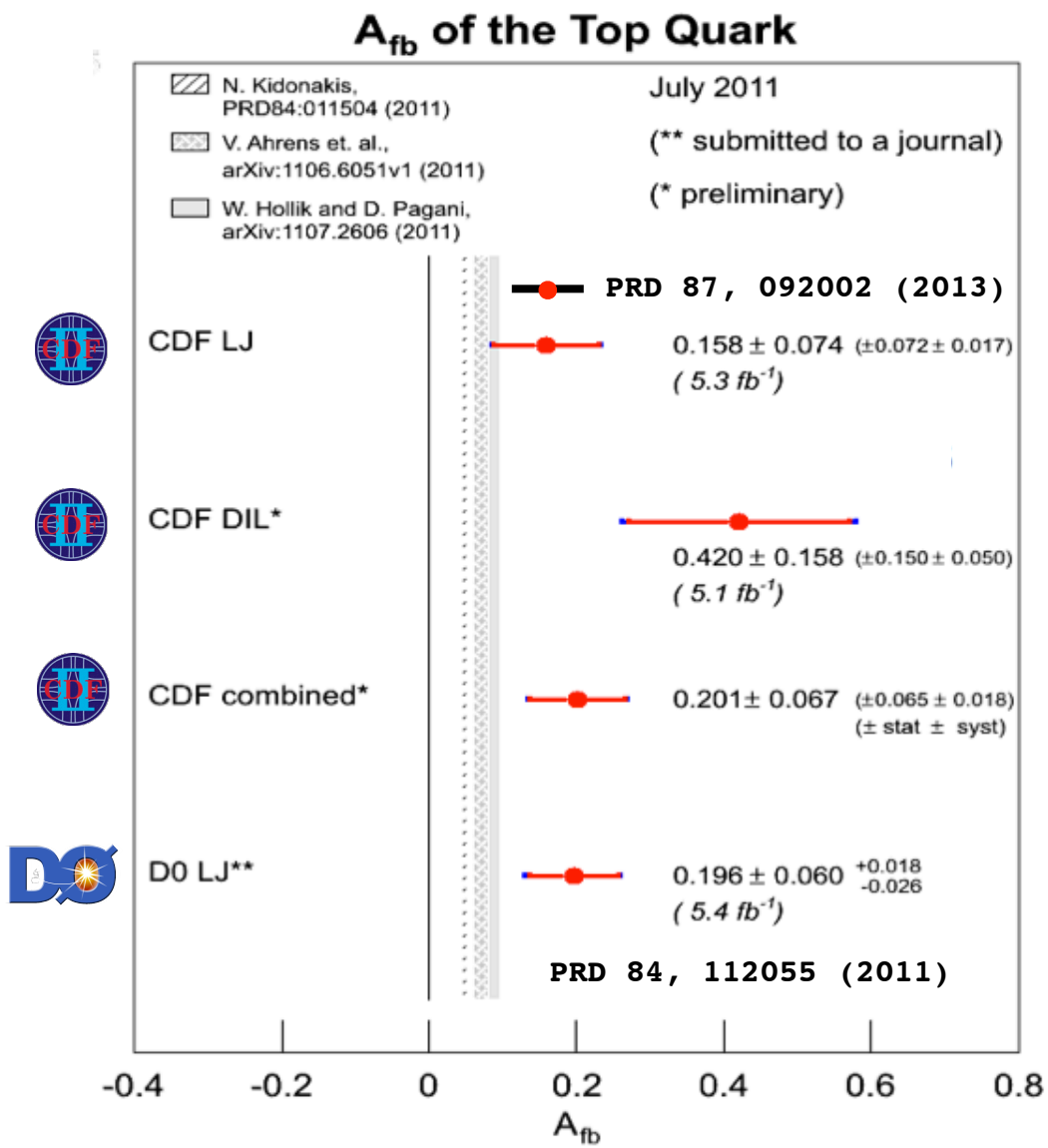






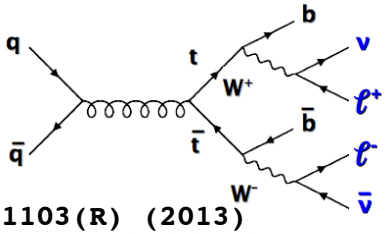
Forward Backward Charge Asymmetry





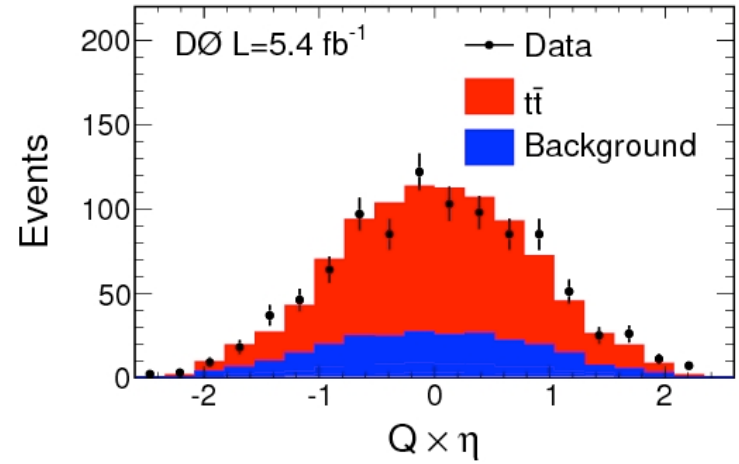
Leptonic Asymmetry

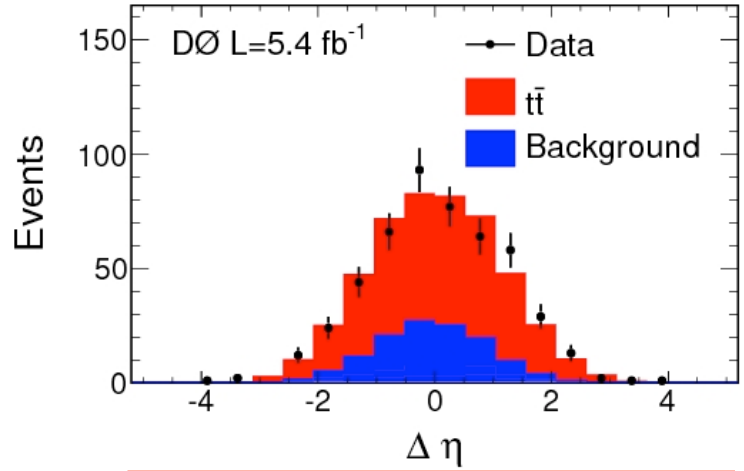
$$A^{l}_{FB} = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$



PRD 87, 011103(R) (2013)

- complementary information

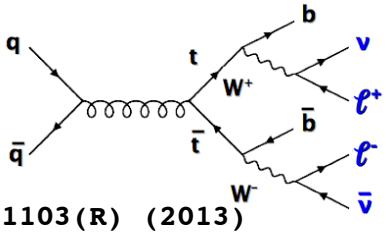




$A^{\ell}_{FB} = 5.8 \pm 5.3\%$

Leptonic Asymmetry

$$A^{l}_{FB} = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$

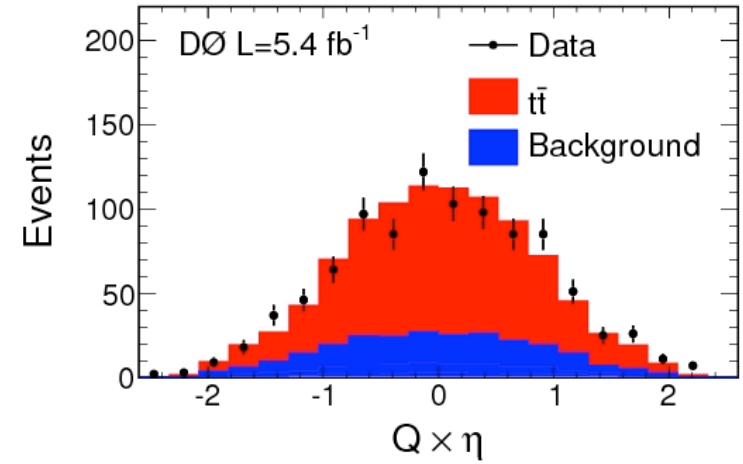


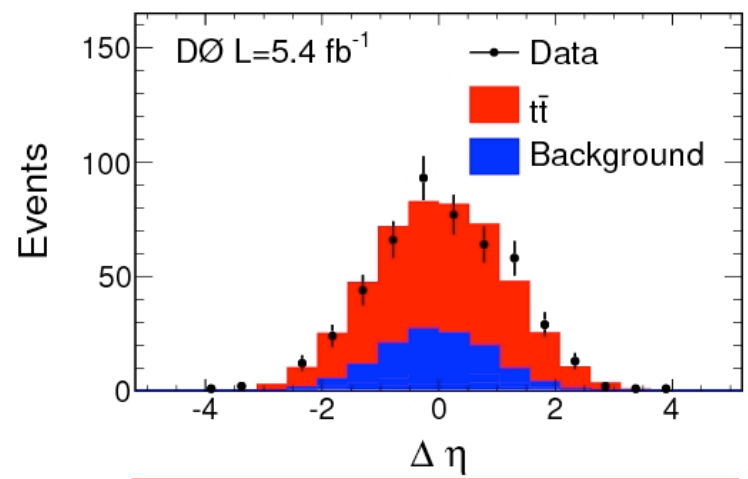
PRD 87, 011103(R) (2013)

$$A^{ll}_{FB} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}$$

$$A^{CP}_{FB} = \frac{N_{l^+}(\eta > 0) - N_{l^-}(\eta < 0)}{N_{l^+}(\eta > 0) + N_{l^-}(\eta < 0)}$$

- **complementary information**





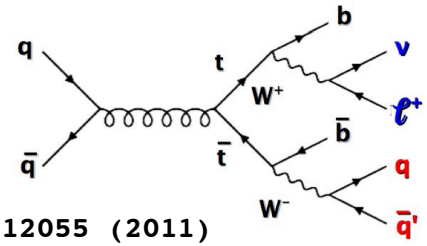
DØ	Unfolded (%)	Predicted NLO QCD+QED (%)
A_{FB}^{l}	5.8±5.3	4.7±0.1
A_{FB}^{ll}	5.3±8.4	6.2±0.2
A_{FB}^{CP}	-1.8±5.3	-0.3±0.1

A^{ℓ}_{FB} = 5.8 ± 5.3%

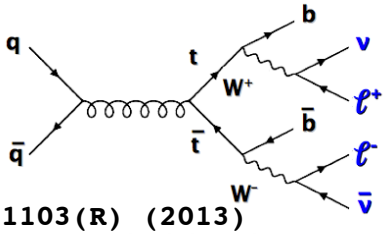
⇒ **good agreement with SM**

statistically limited

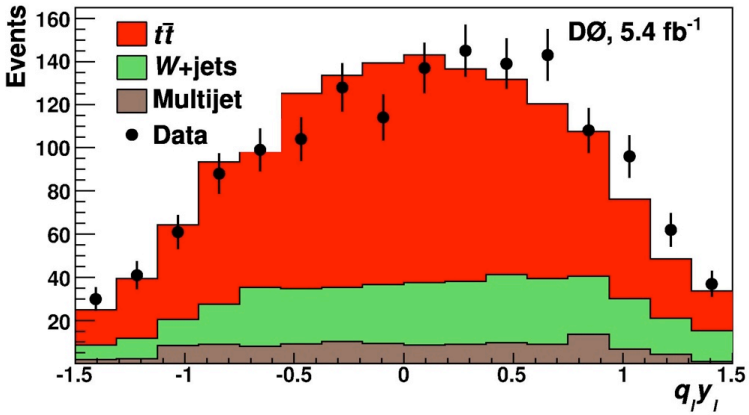
Leptonic Asymmetry

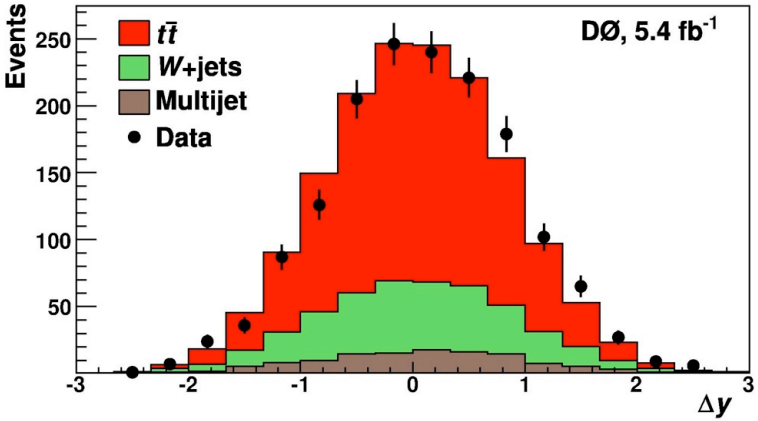


$$A^{l}_{FB} = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$



PRD 84, 112055 (2011)





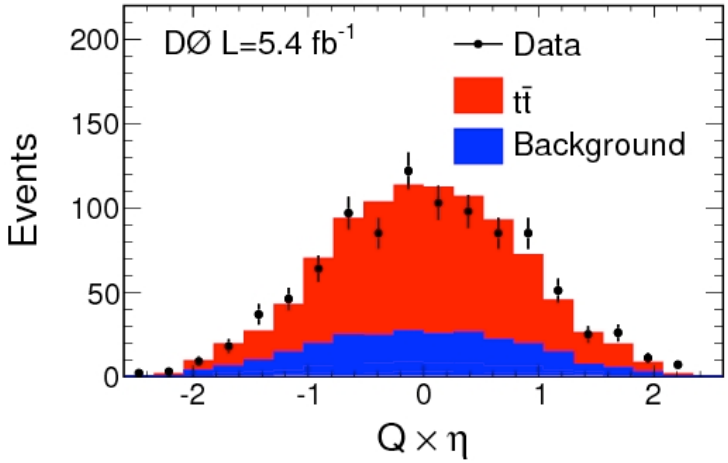
$A^{\ell}_{FB} = 15.2 \pm 4.0\%$

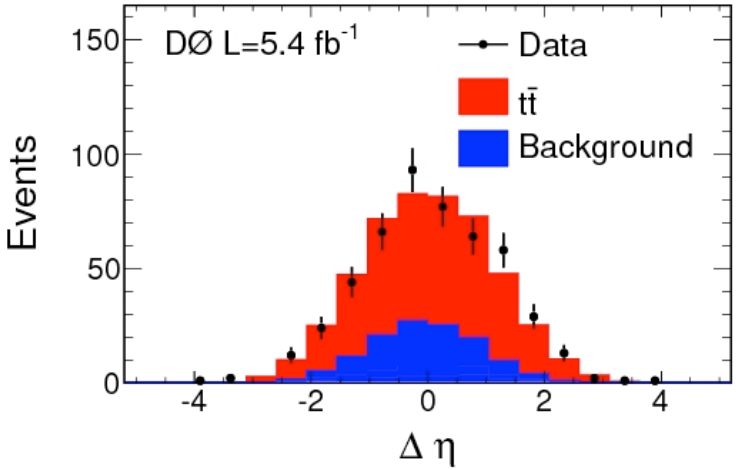
- complementary information

CDF:

$A^{\ell}_{FB} = 9.4^{+3.2}_{-2.9}\,\%$

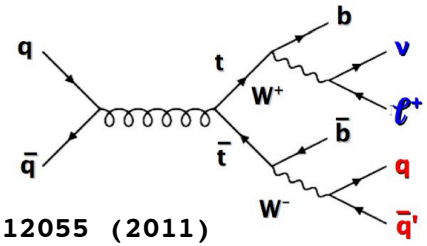
PRD 87, 011103(R) (2013)



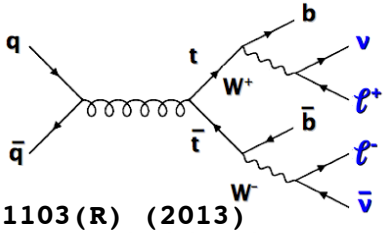


$A^{\ell}_{FB} = 5.8 \pm 5.3\%$

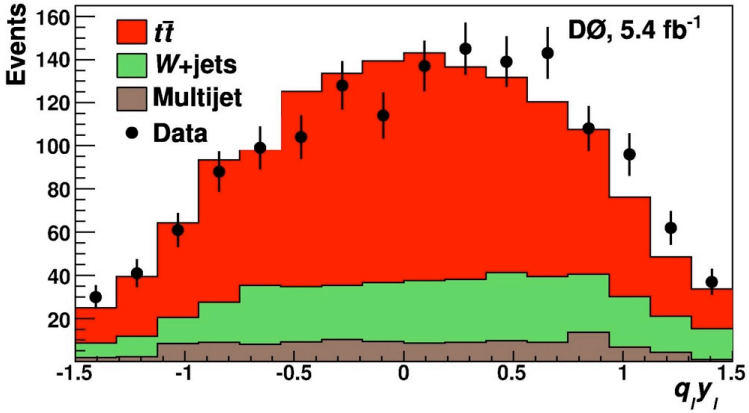
Leptonic Asymmetry

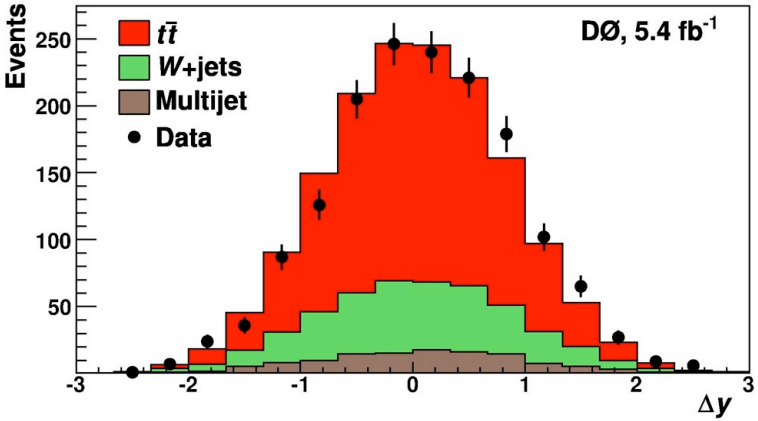


$$A^{l}_{FB} = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$



PRD 84, 112055 (2011)





A^{ℓ}_{FB} = 15.2 ± 4.0%

- complementary information

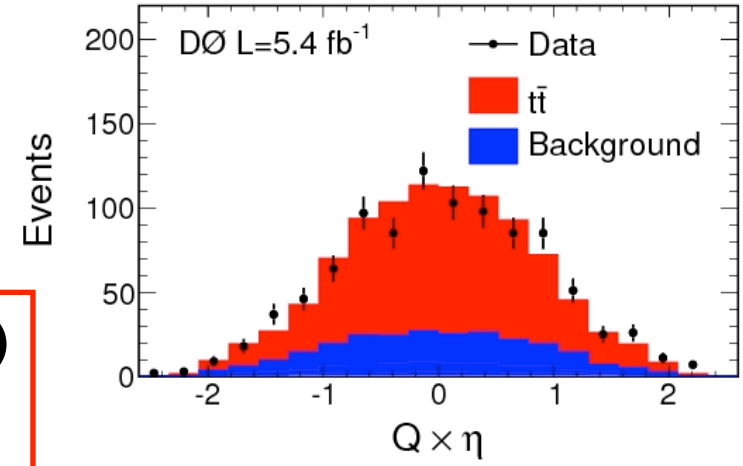
2.2σ

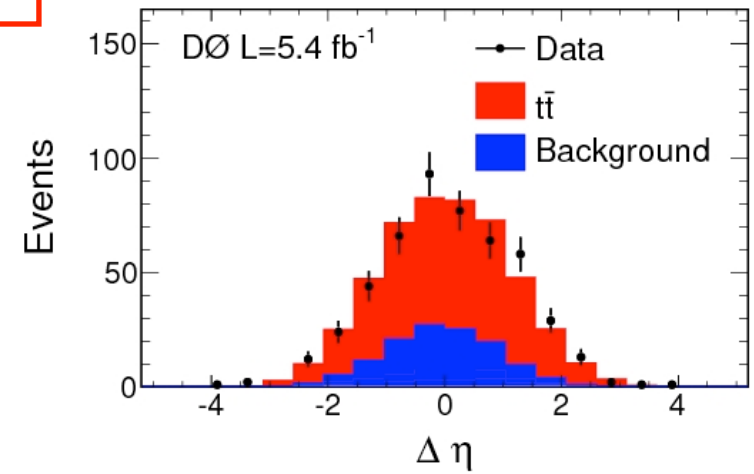
A^{ℓ}_{FB} (combined) = 11.8 ± 3.2%

QCD+EWK: A^{ℓ}_{FB} = 4.7 ± 0.1%

CDF: $A^{\ell}_{FB} = 9.4^{+3.2}_{-2.9}$ %

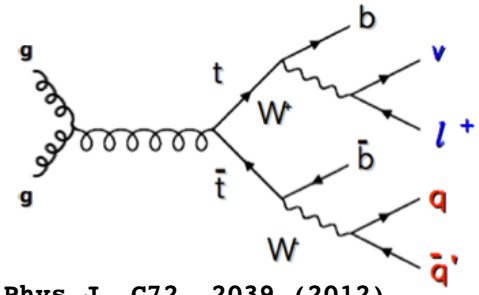
PRD 87, 011103(R) (2013)





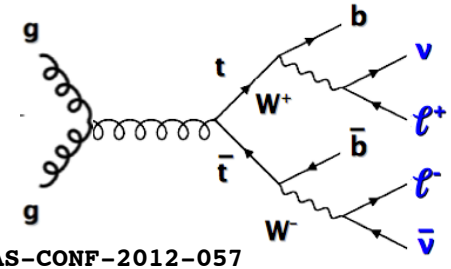
A^{ℓ}_{FB} = 5.8 ± 5.3%

Charge Asymmetry: LHC

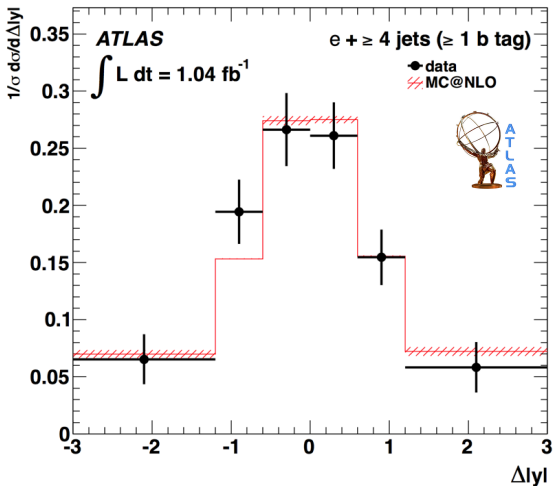


Eur.Phys.J. C72, 2039 (2012)

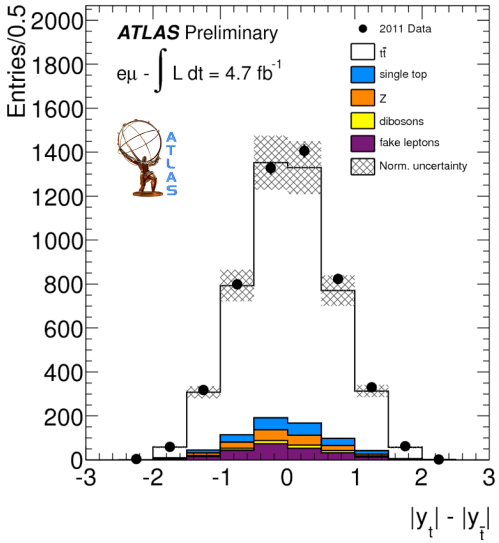
$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$



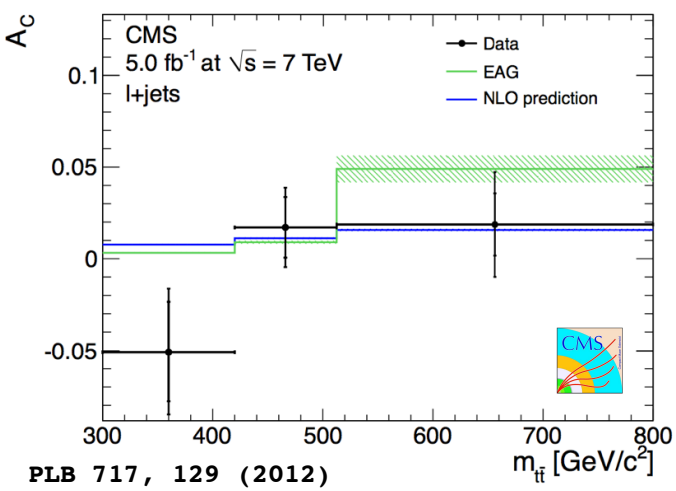
ATLAS-CONF-2012-057



A_C (l+jets) = −1.8 ± 3.6%
A_C (l+jets) = +0.4 ± 3.7%



A_C (dilepton) = 5.7 ± 2.8%
A_C (dilepton) = 5.0 ± 4.3%

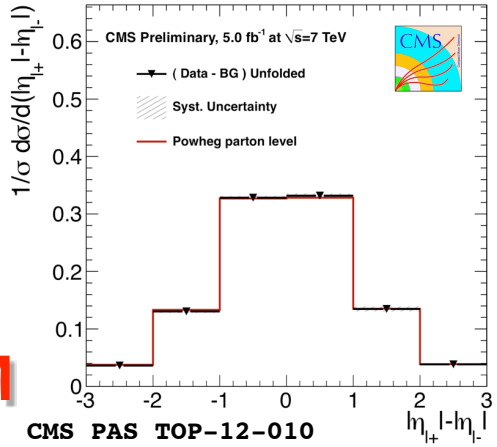


PLB 717, 129 (2012)

A_C (combined) = 2.9 ± 2.8%

MC@NLO:
A_C = 0.6 ± 0.2%

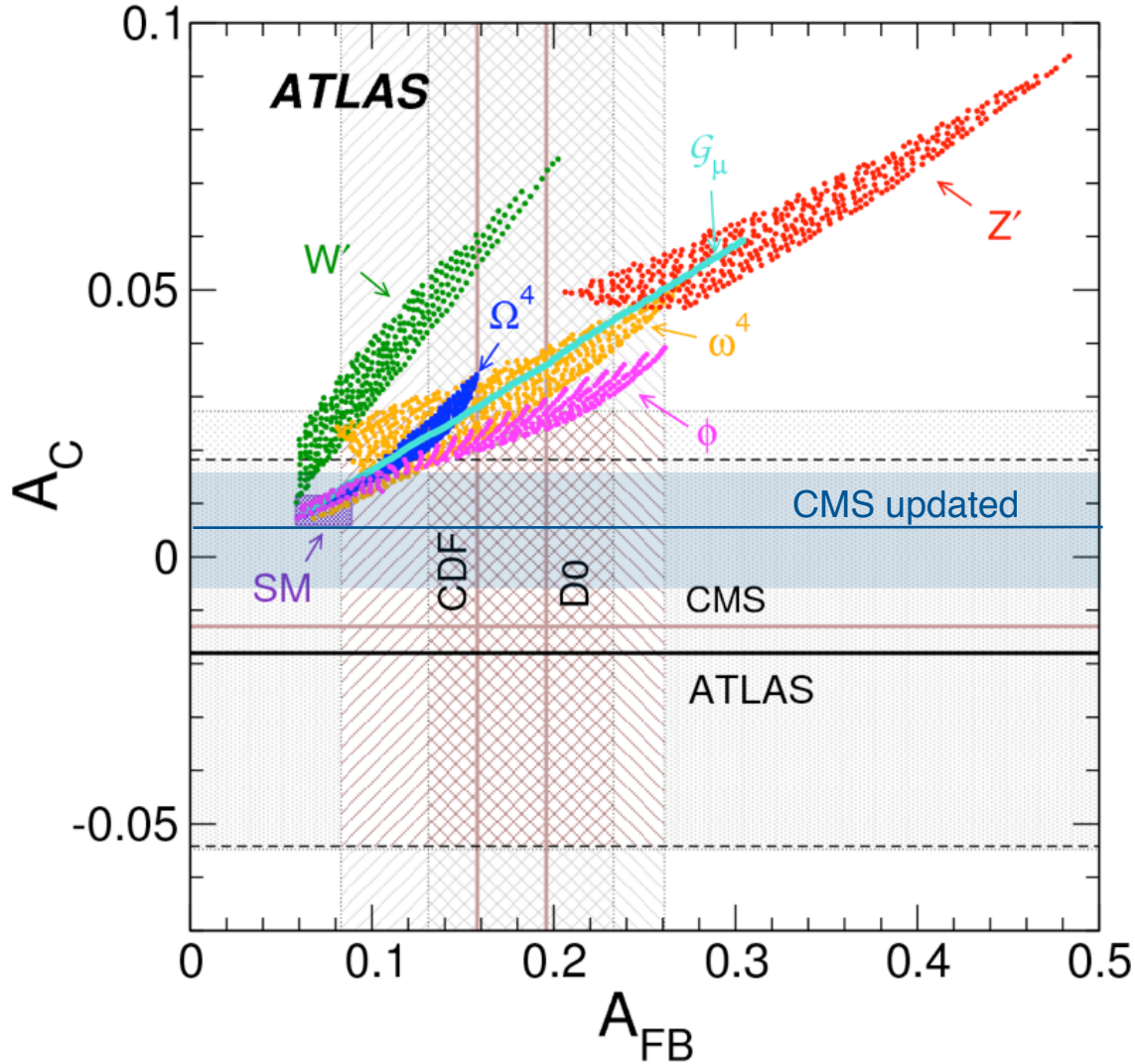
⇒ good agreement with SM



CMS PAS TOP-12-010

FB vs Charge Asymmetry

Eur.Phys.J. C72, 2039 (2012)



→ **Tevatron excess will be further investigated**

Outline

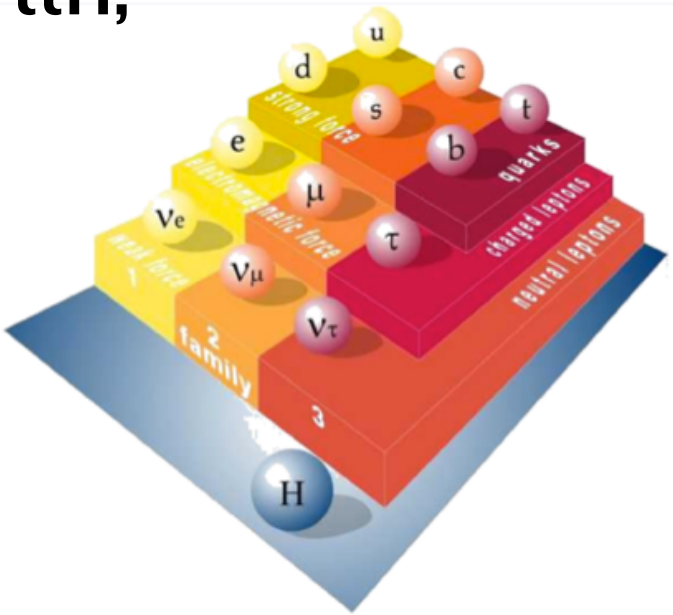
Introduction
Top Pair Production
Differential Cross Sections
Single Top Production
Top Pair Asymmetries
Conclusions

Summary

- **we are in the middle of the precision top physics era**
  - top pair cross section (5.4% Tevatron, 4% LHC)
  - V_{tb} (8% Tevatron, 5% LHC)
  - differential cross sections: challenging NLO QCD calculations
- new processes: t-channel single top (observation), tW (evidence), ttZ (evidence), tt+HF, ttγ, ttH, tt+gap fraction, ...

→ good agreement with SM

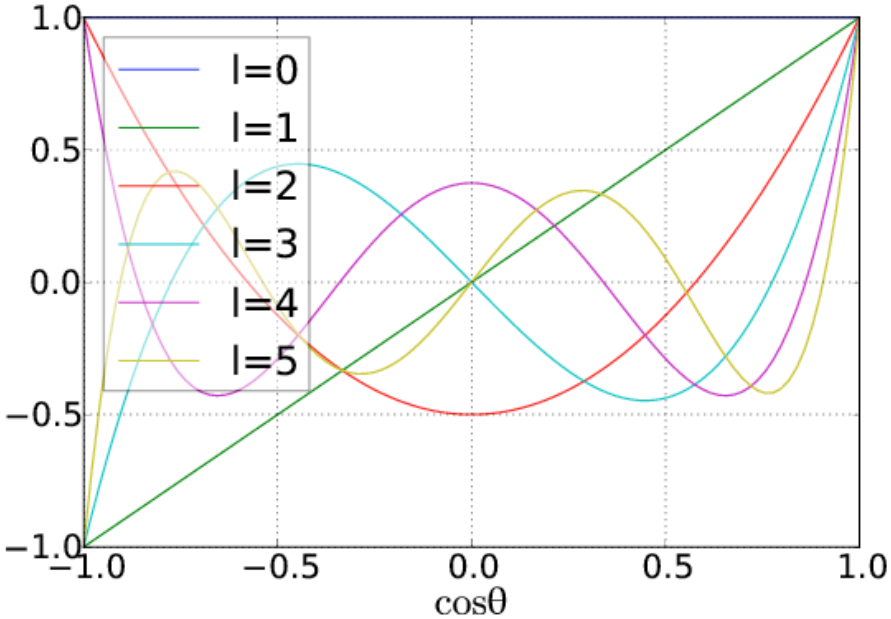
- top pair asymmetry:
  - good agreement at the LHC
  - puzzling situation at the Tevatron, more analyses soon ready

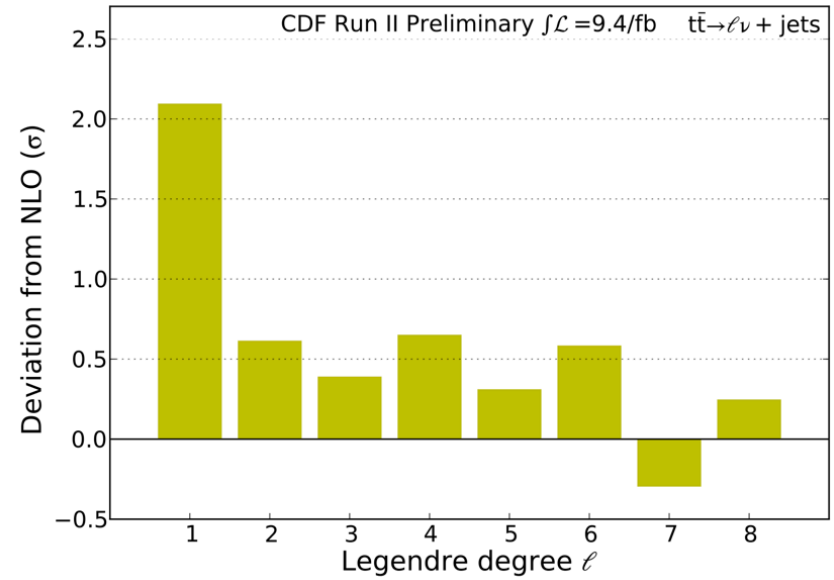


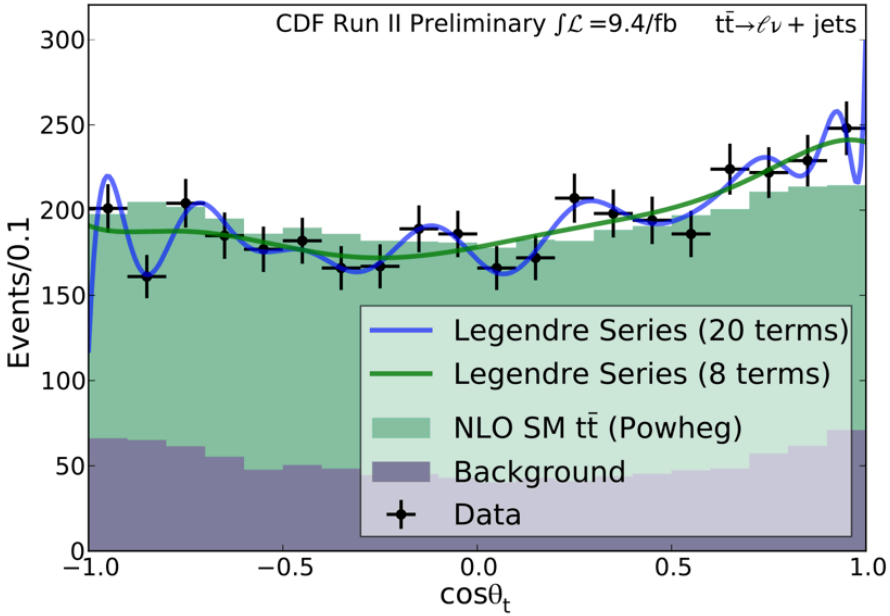
Backup

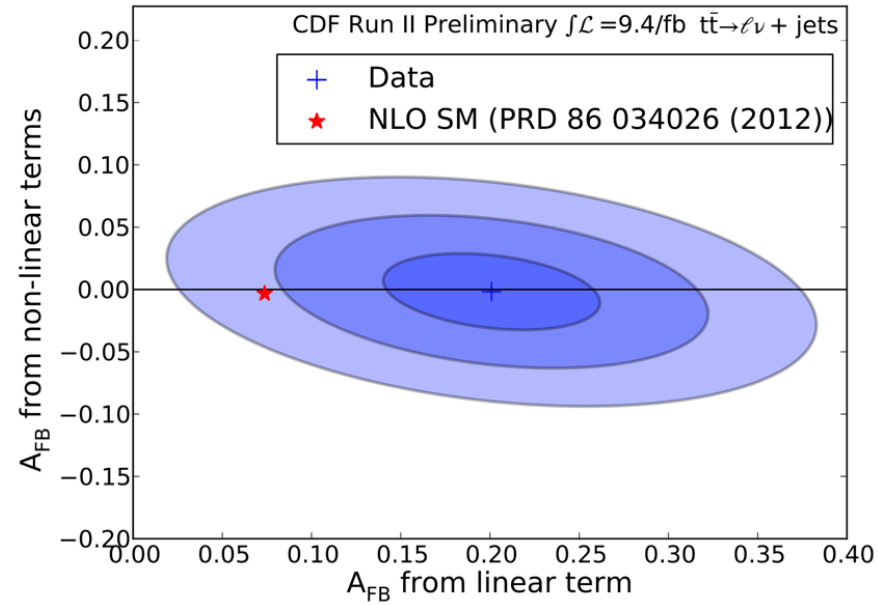
Legendre Polynomials

CDF-CONF 10974

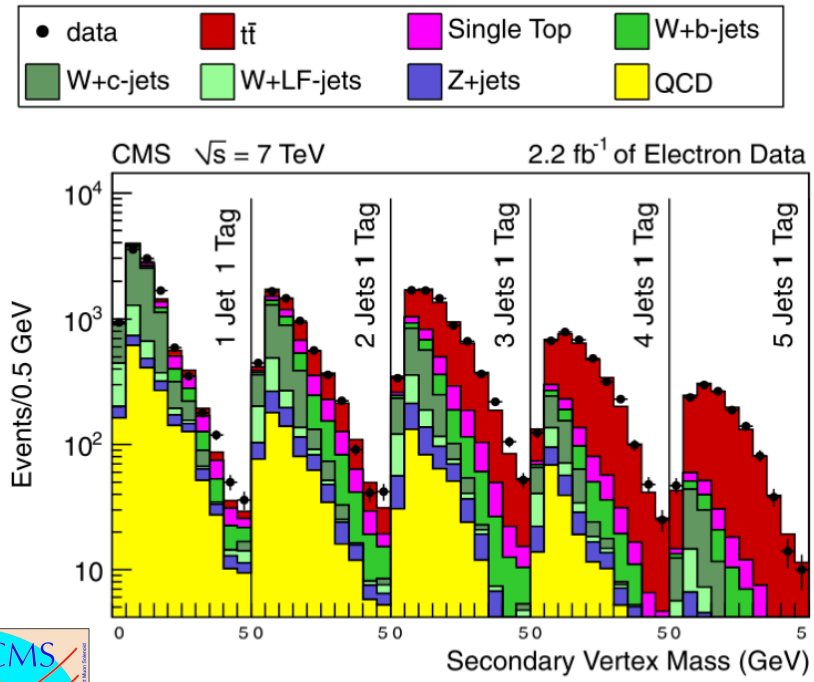


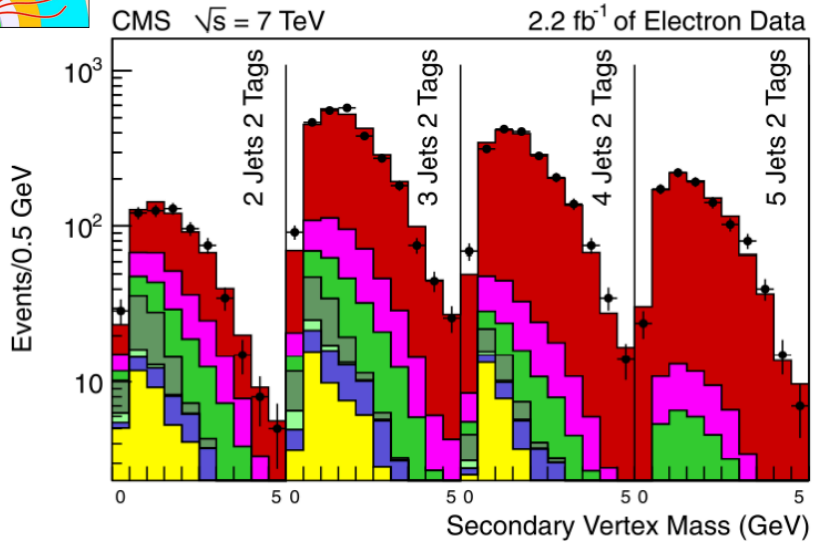




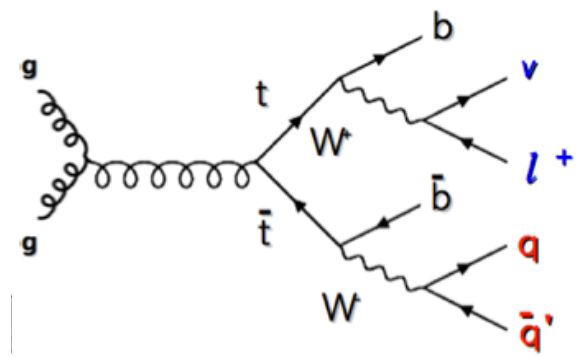


Lepton+Jets Cross Section

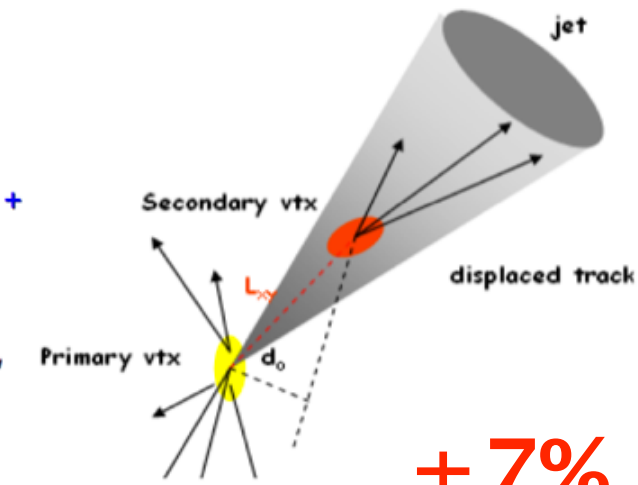




Source	Electron channel	Muon channel	Combined analysis
Quantity	Uncertainty (%)		
Lepton ID/reconstruction/trigger efficiency	3.0	2.0	3.0
$\not{E}_T$ resolution due to unclustered energy	0.9	0.3	0.8
Jet energy resolution	0.5	0.5	0.6
$t\bar{t}$ + jets renorm./fact. scales	3.5	4.3	4.3
$t\bar{t}$ + jets ME to PS matching	2.2	1.8	2.2
Pileup	0.5	0.2	0.6
Parton distribution function choice	0.3	0.3	0.3
QCD multijet SVM distribution	1.4	0.4	0.6
Subtotal	5.5	5.1	5.9
Nuisance parameter	Uncertainty (%)		
Jet energy scale	3.9	3.0	2.4
b-tagging efficiency and mistag rate	3.5	2.8	2.1
W + jets renorm./fact. scale	1.6	1.5	1.6
Total systematic uncertainty	7.0	6.2	6.5



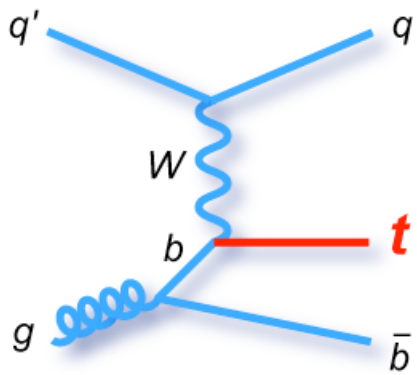
top pairs



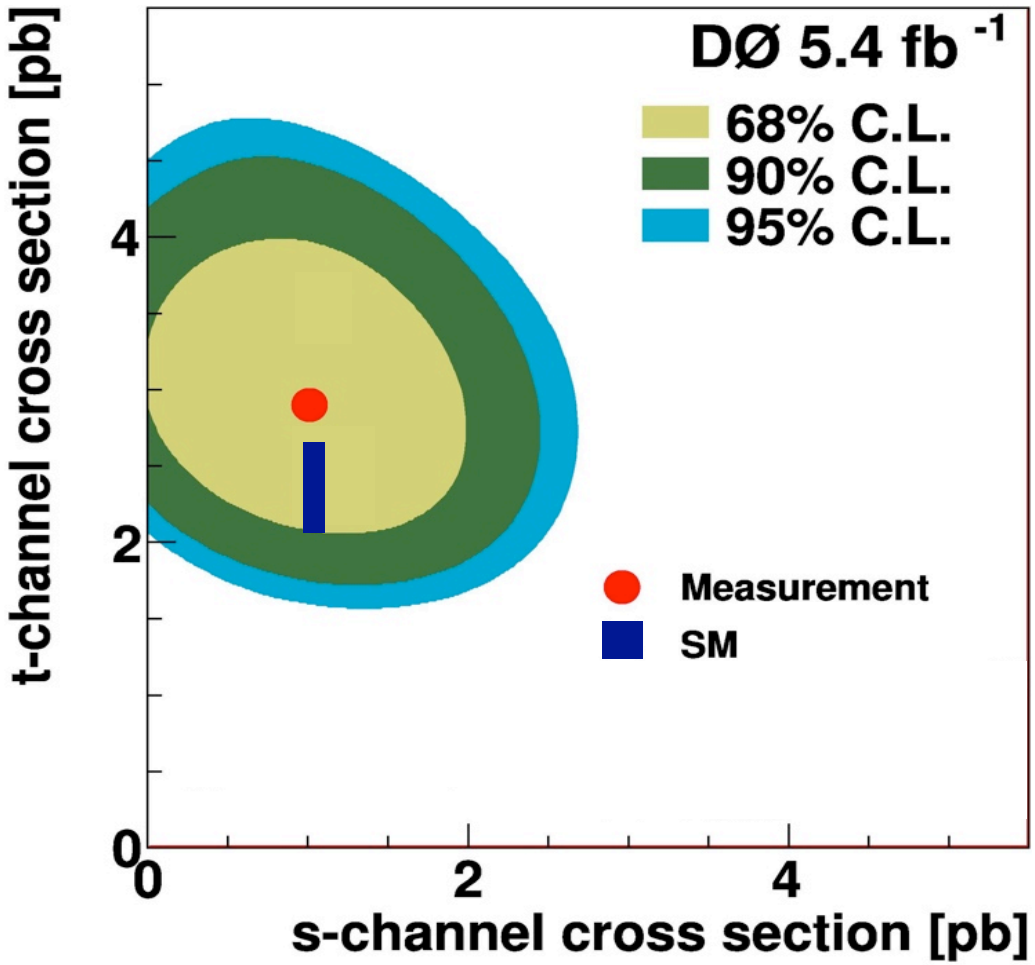
±7%

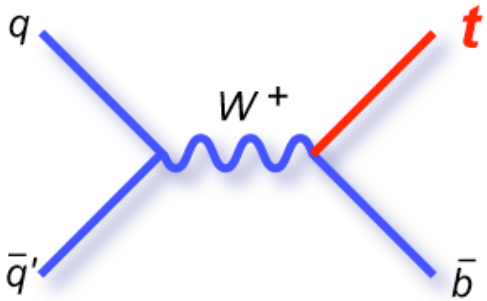
$$\sigma_{t\bar{t}} = 158.1 \pm 2.1\,(\text{stat.}) \pm 10.2\,(\text{syst.}) \pm 3.5\,(\text{lum.})\ \text{pb}$$

Single Top s- vs. t-channel



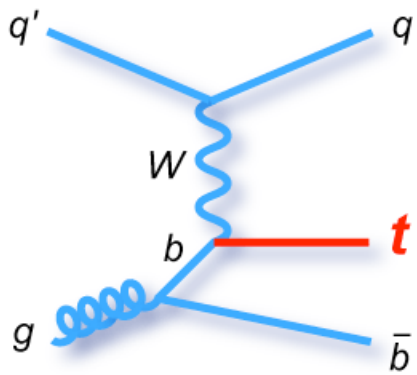
PLB 705, 313 (2011)



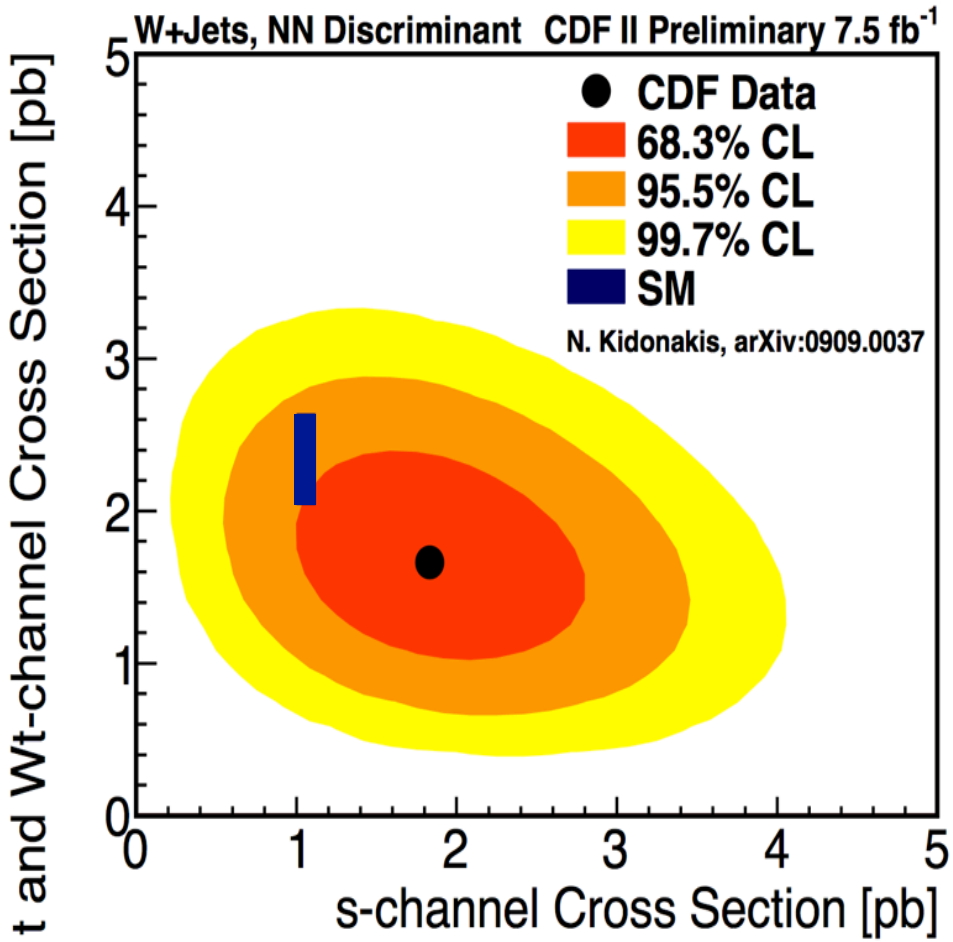


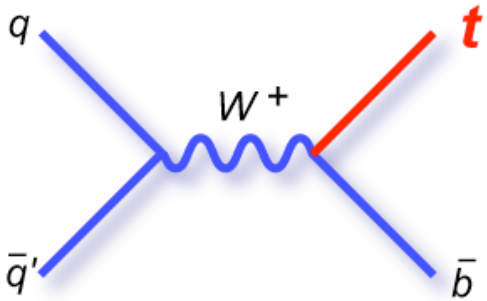
⇒ good agreement with Standard Model

Single Top s- vs. t-channel



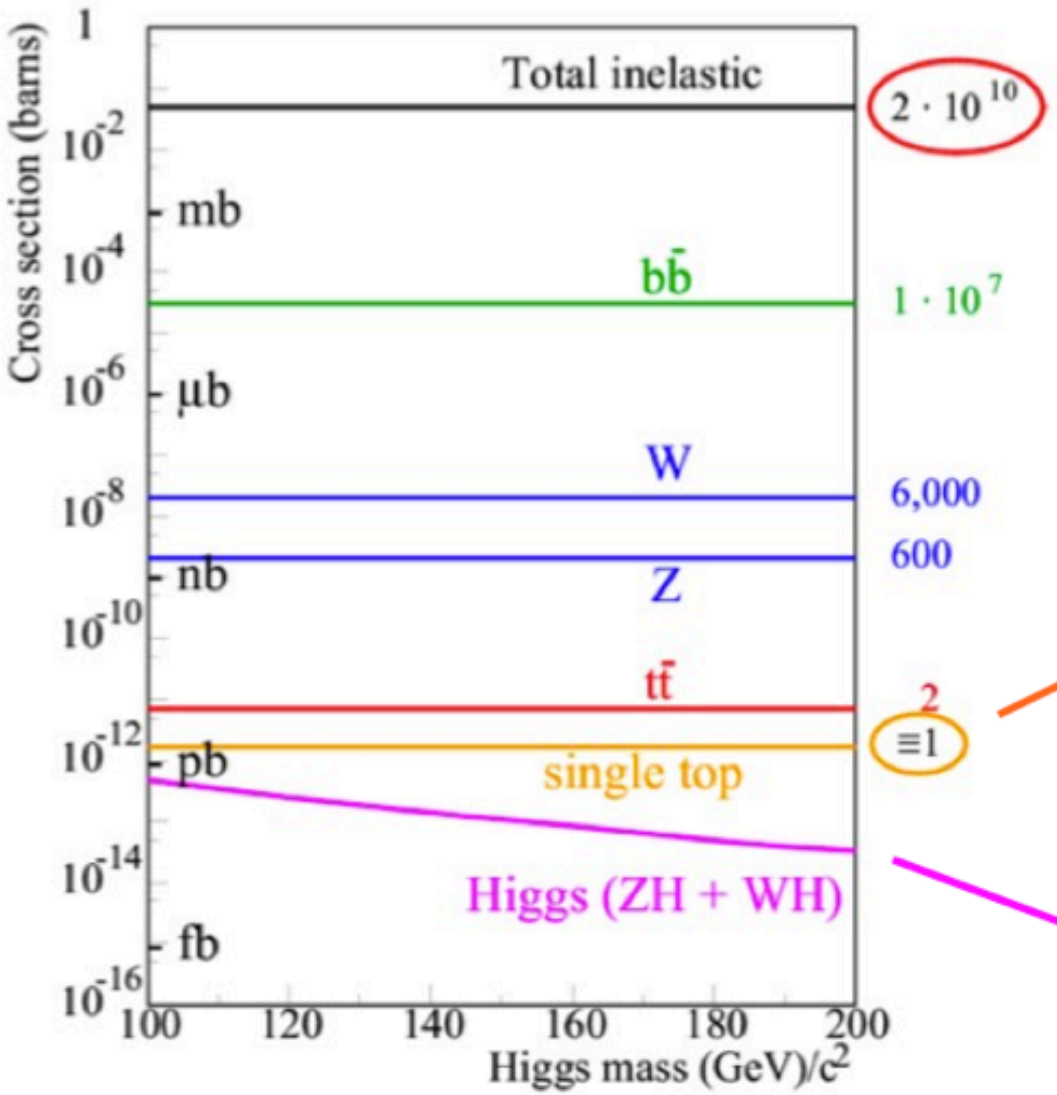
CDF-CONF 10793

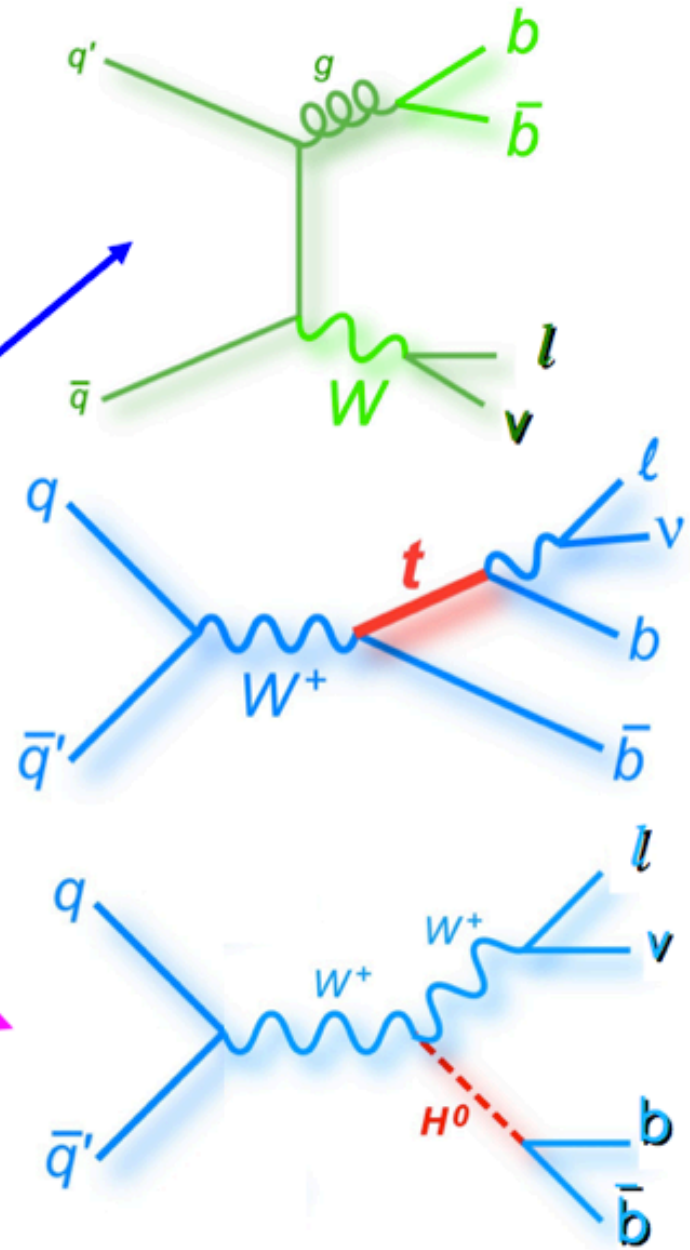




⇒ good agreement with Standard Model

It has been challenging for years...

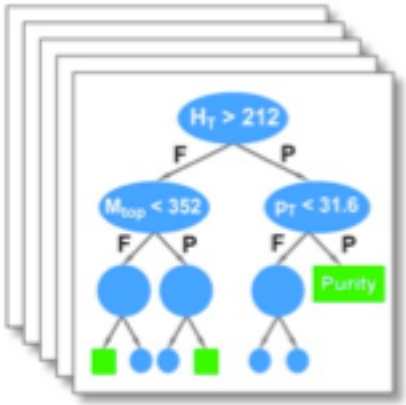




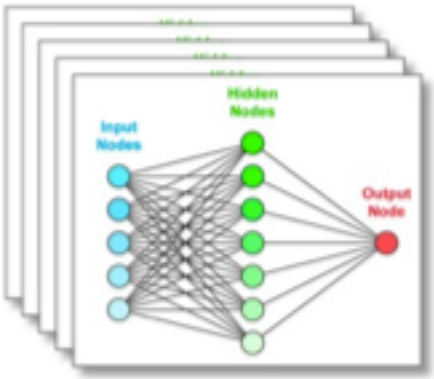
⇒ **multivariate analysis techniques**

Mulitvariate Analyses

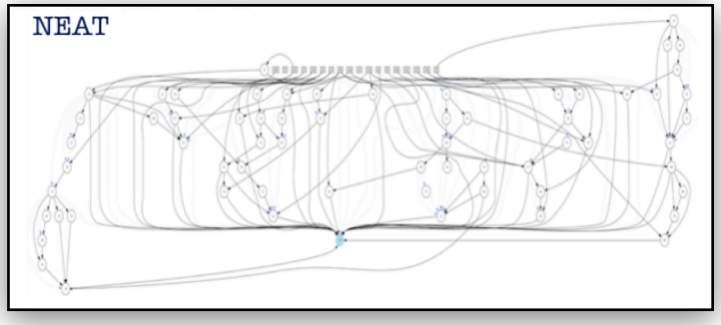
Boosted Decision Trees



Neural Networks



Neuroevolution of Augmenting Topologies



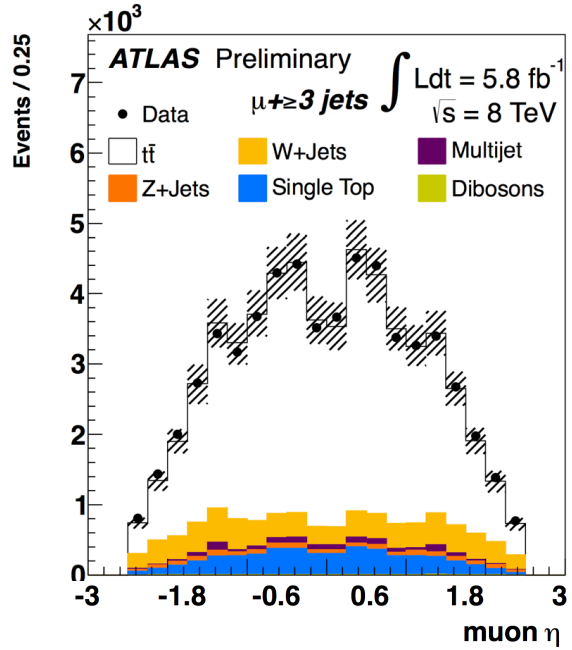
Lepton+Jets Topological Cross Section

powerful test of QCD and search for new physics!

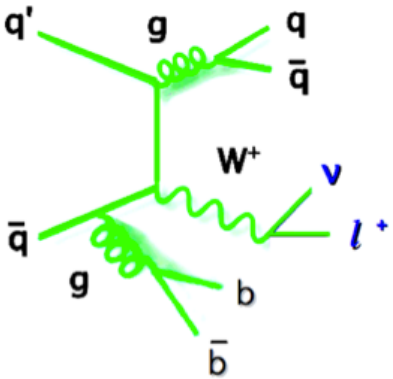
for separation between signal and background use variables such as:

energy-dependent quantities:
e.g. scalar sum of transverse momenta

angular dependent:
e.g. pseudorapidty, aplanarity

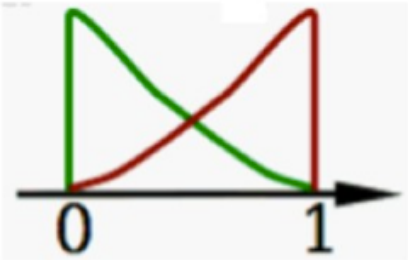


W+jets

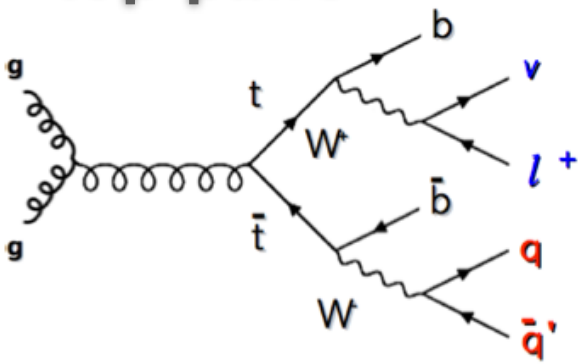


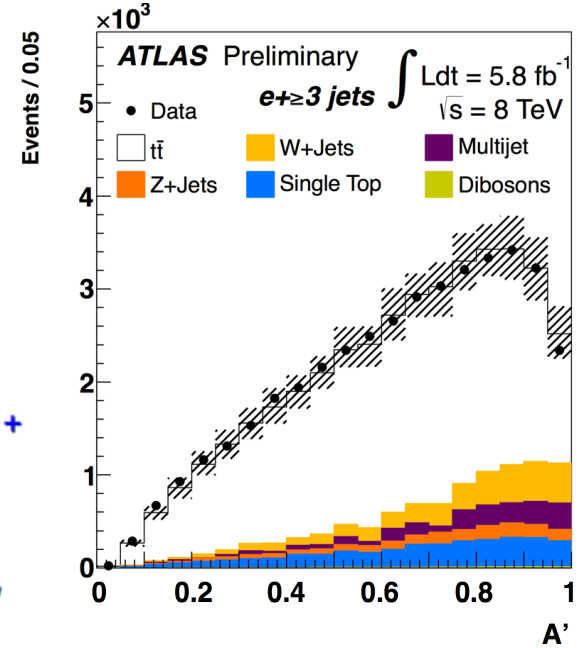
Likelihood Discriminant

background **signal**



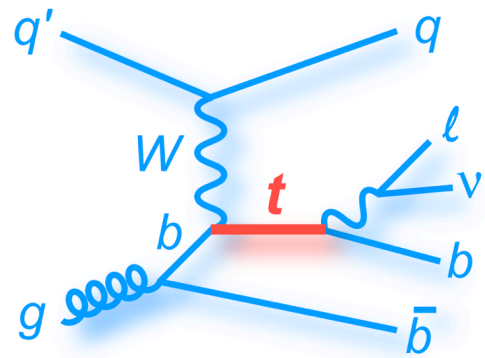
top pairs

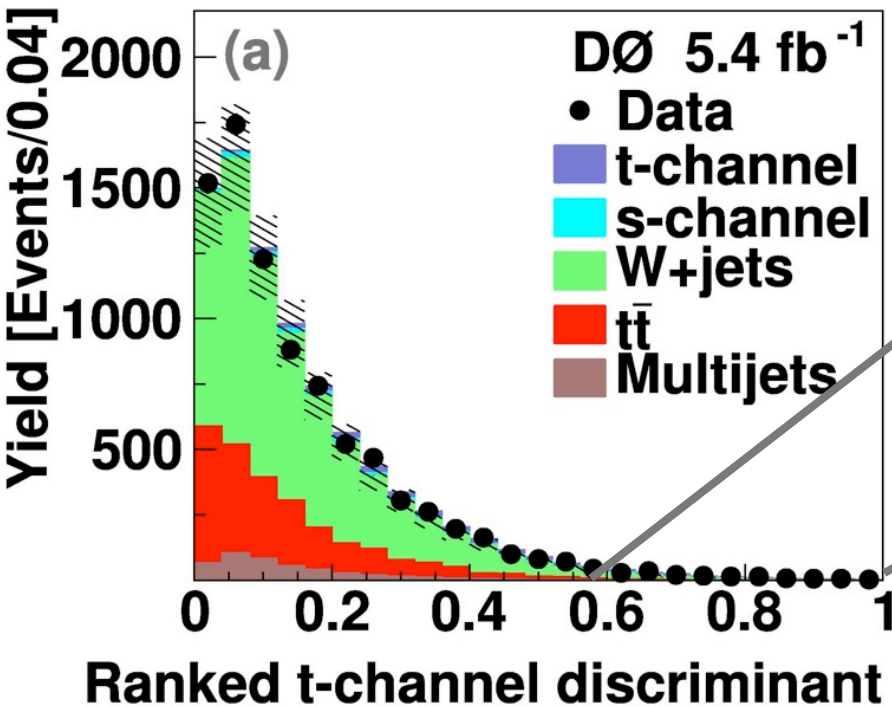


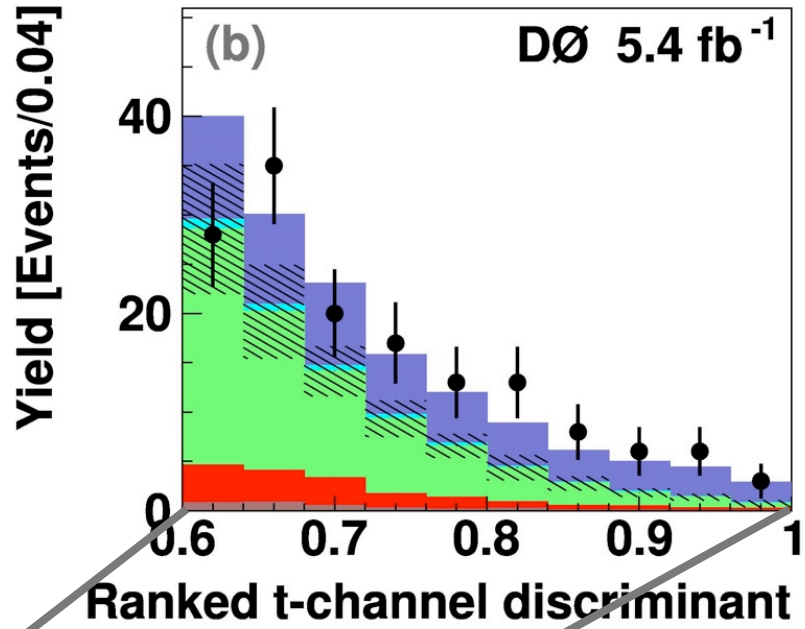


Single Top t-channel Production

- remove s/t channel constraint which could be changed by new physics
- train multivariate analysis for t-channel
- measure s- and t-channel simultaneously







PLB 705, 313 (2011)

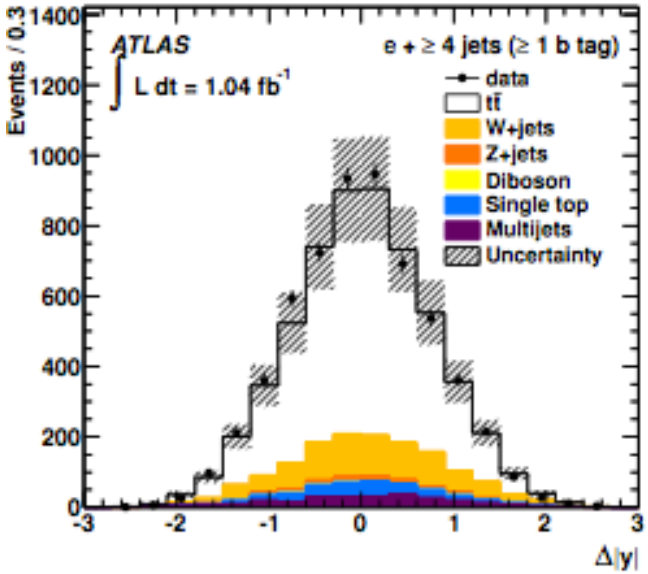
σ_t = 2.12±0.16 pb

NNNLO$_{approx}$, m_t = 172.5 GeV ±20%

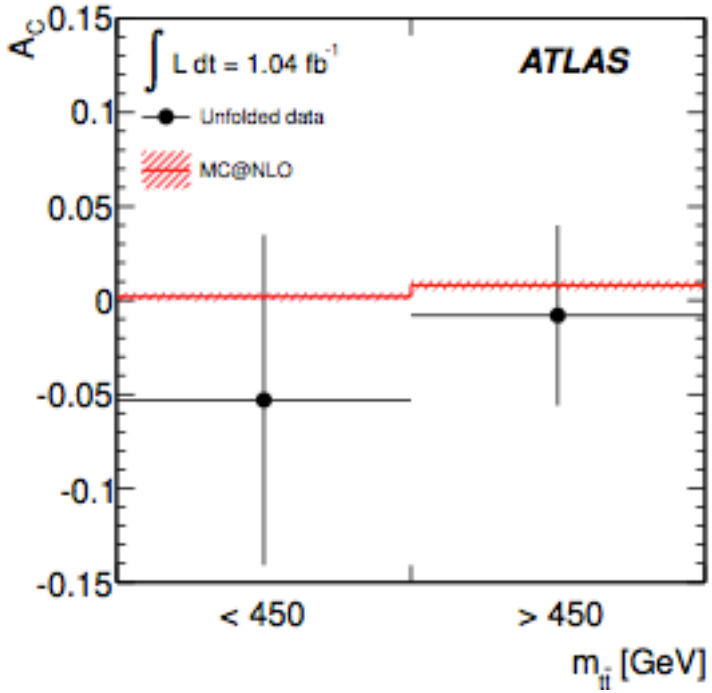
σ(t-channel)=2.90±0.59 pb

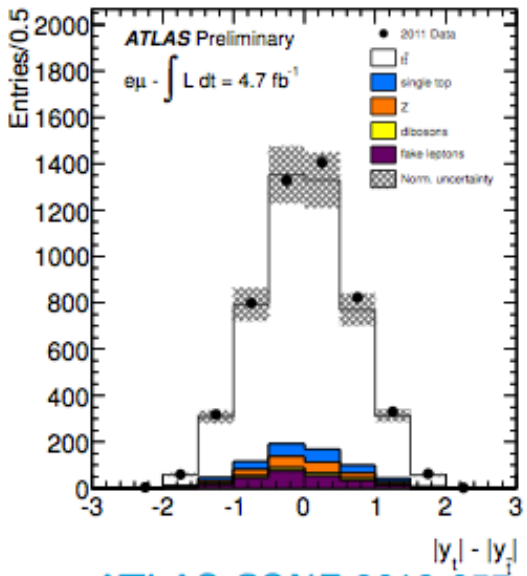
observation with 5.5σ

Charge Asymmetry: LHC



$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$





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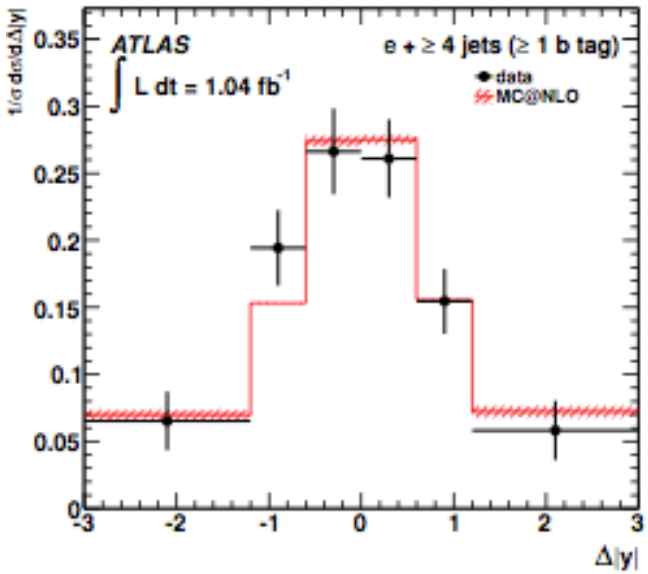
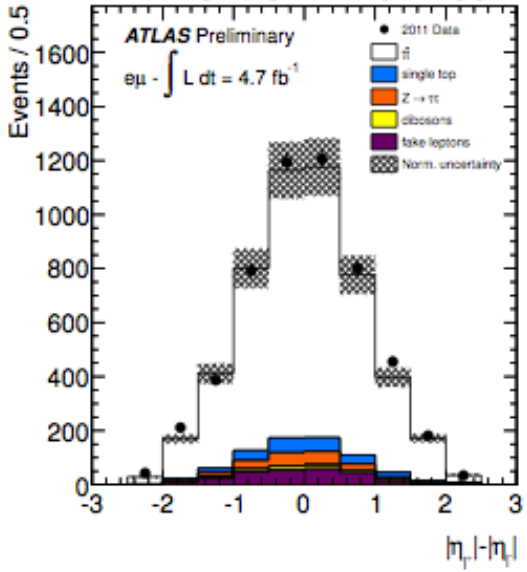




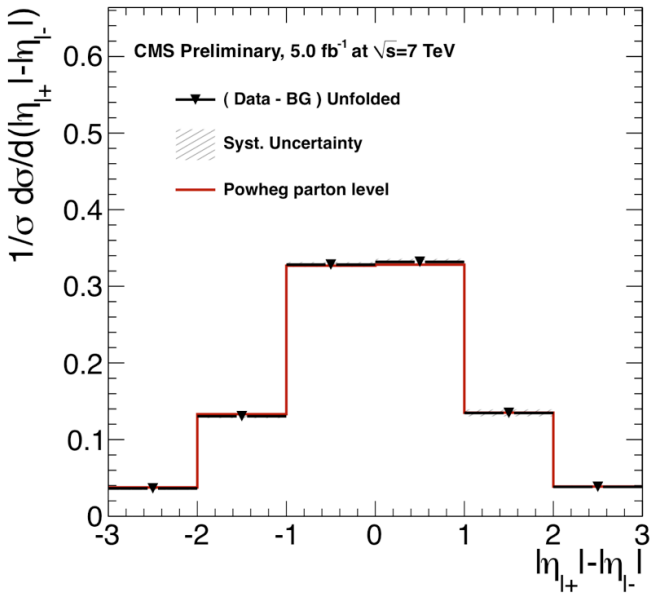
A_C (combined) = 2.9 ± 2.8%

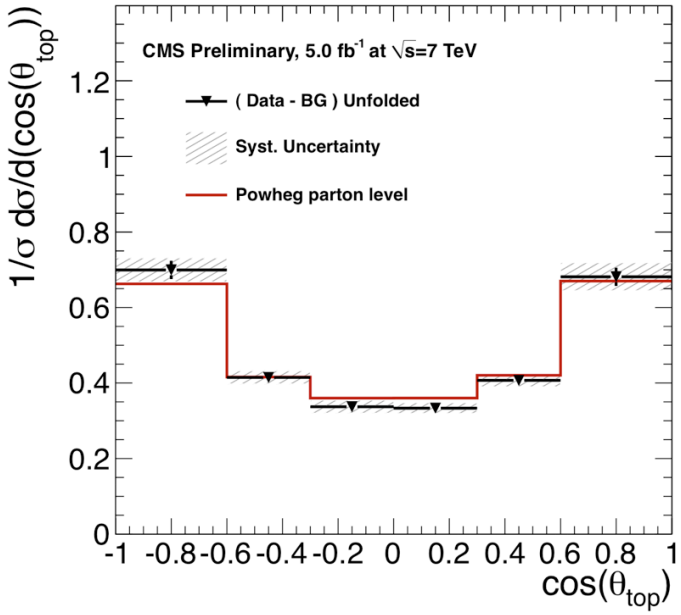
MC@NLO:
A_C = 0.6 ± 0.2%

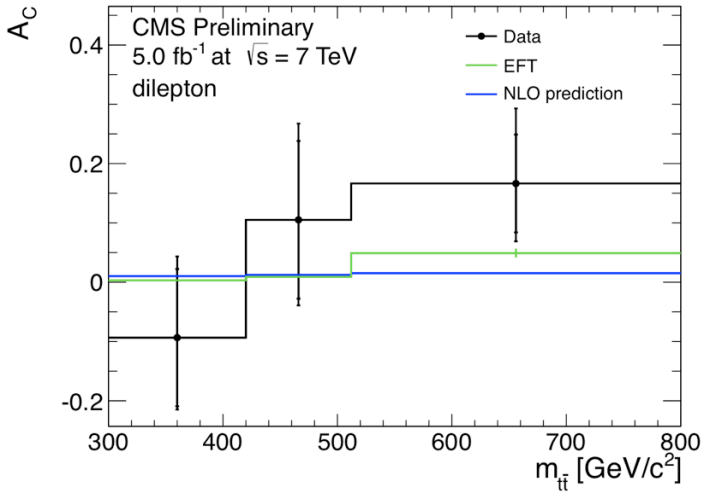
A_C (l+jets) = −1.8 ± 3.6%

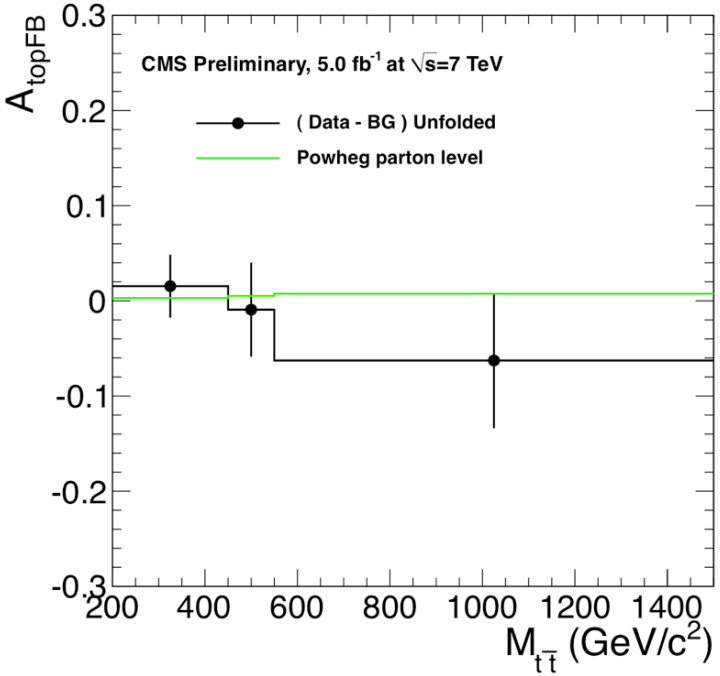
A_C (dilepton) = 5.7 ± 2.8%

FB vs Charge Asymmetry



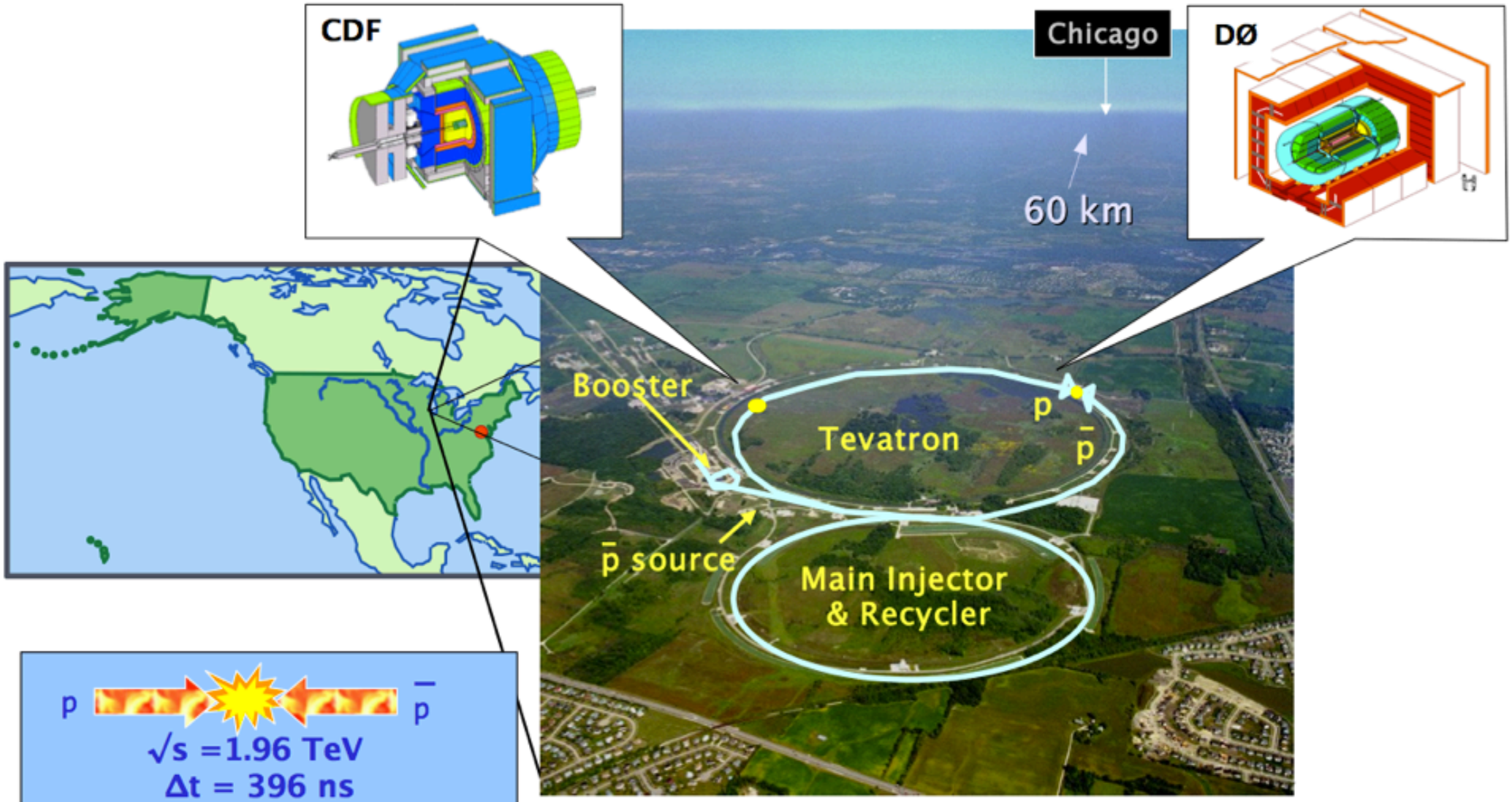






→ **Tevatron excess will be investigated with full dataset**

The Tevatron $p\bar{p}$ Collider at Fermilab



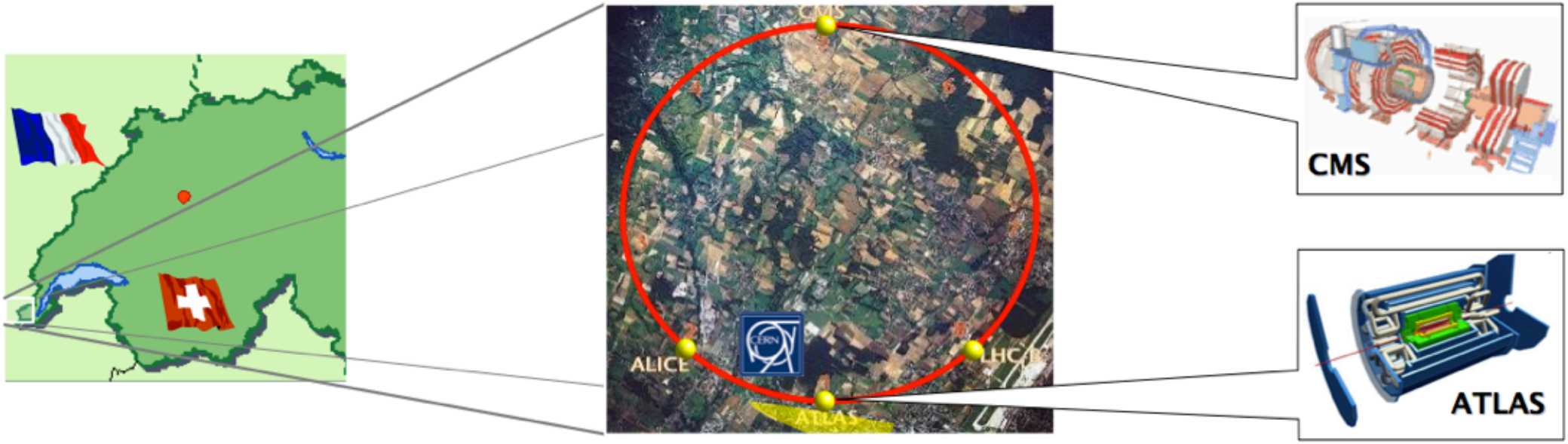
$\sqrt{s}$ =1.96 TeV

Δt = 396 ns

Run I 1987 (92)–95

Run II 2001–11: 100x larger dataset at increased energy

The LHC pp Collider at CERN

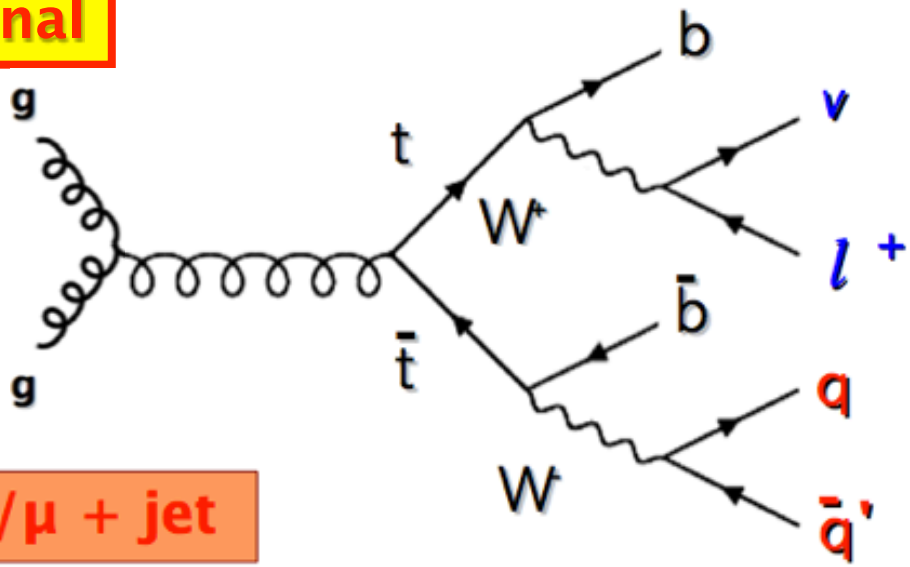


The Large Hadron Collider:

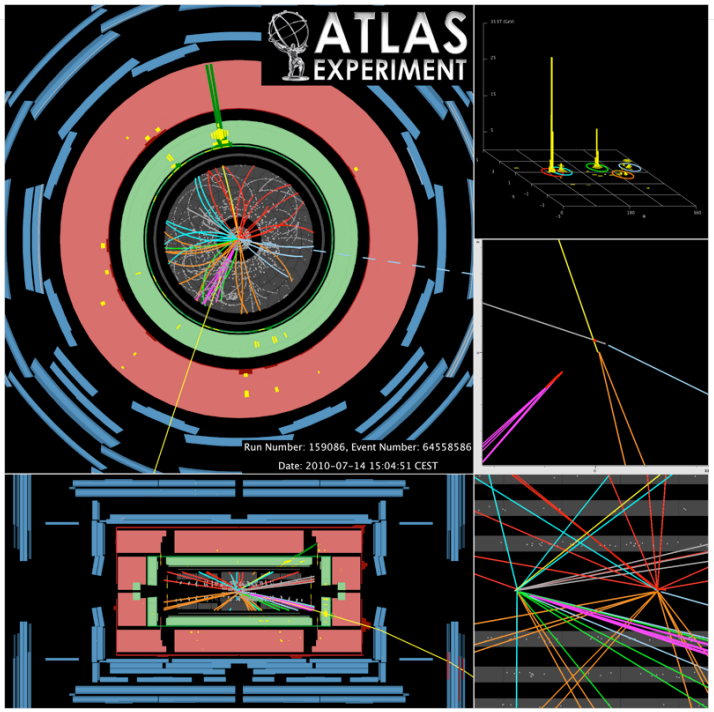
- proton–proton collider
- high energy: $\sqrt{s}$ = 7 TeV
- since 2012: $\sqrt{s}$ = 8 TeV
- 2014–2030??: $\sqrt{s}$ = 13 TeV

Lepton+jets Signatures

signal

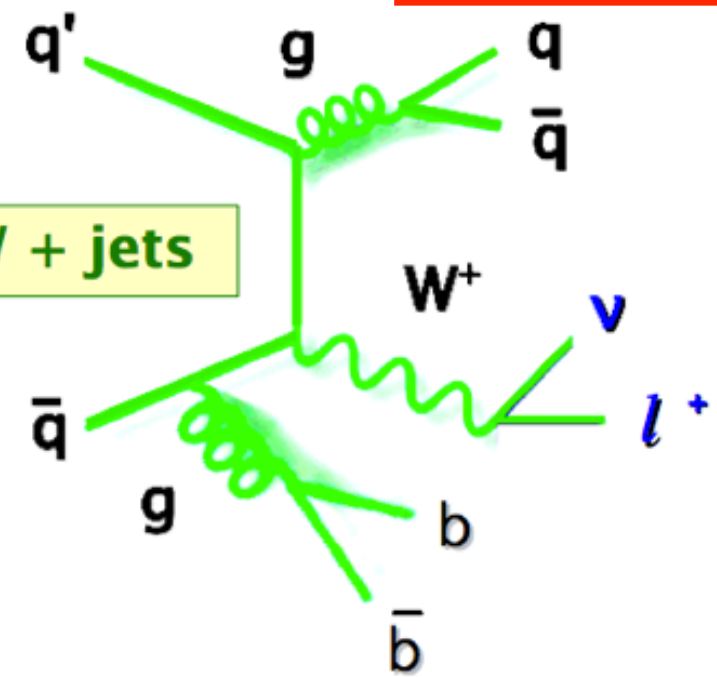


e/μ + jet

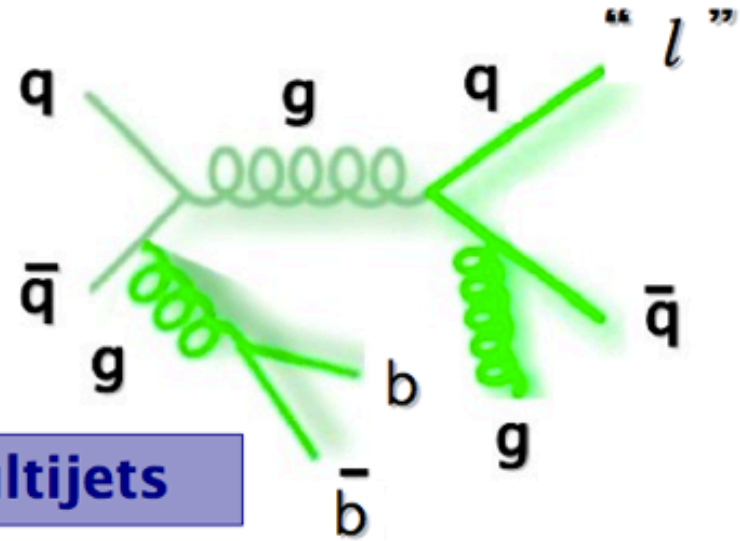


background

W + jets

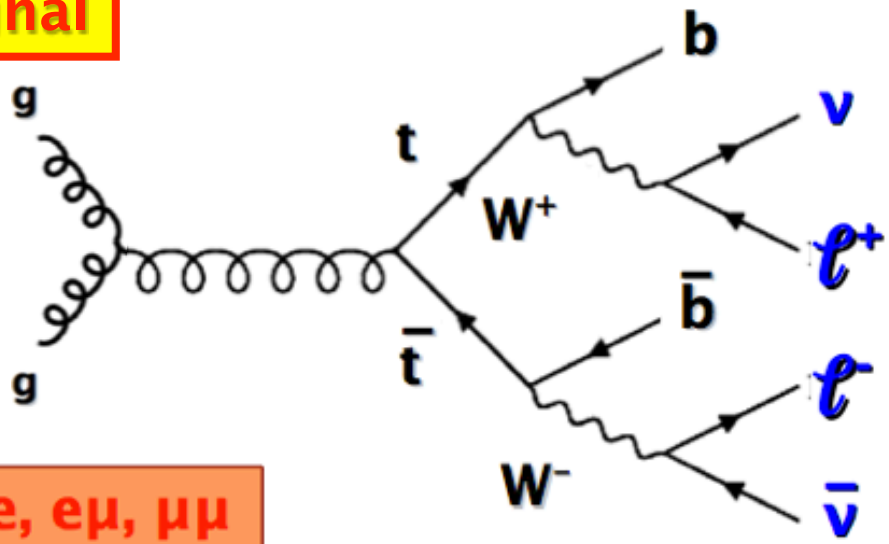


multijets

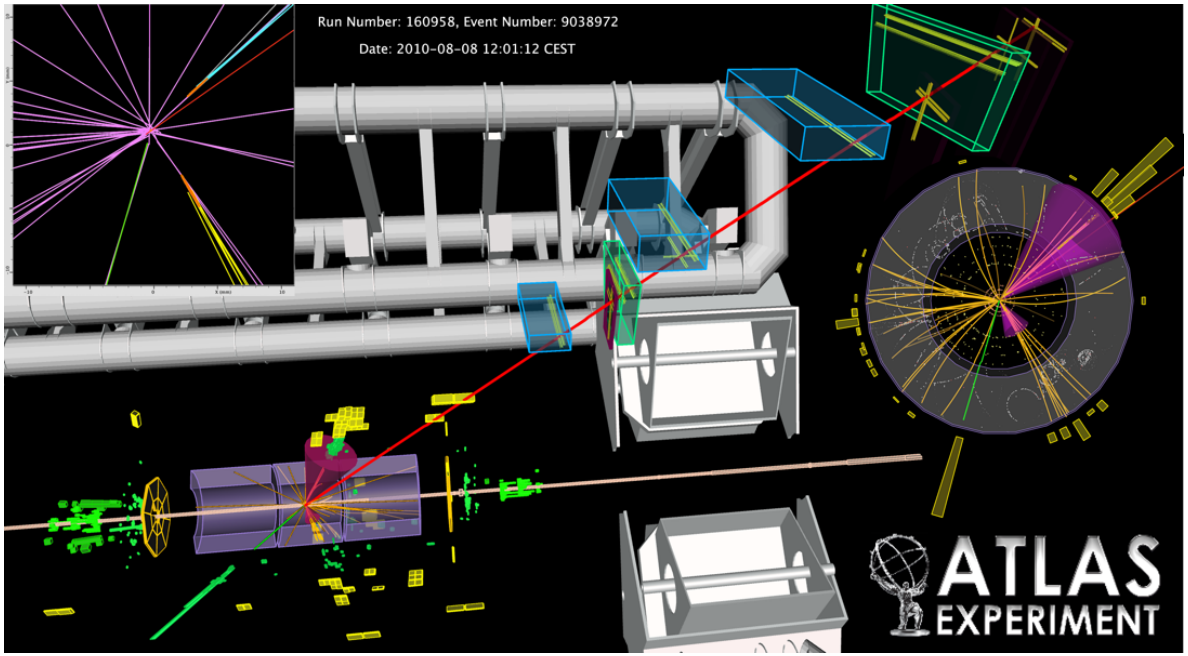


Dilepton Signatures

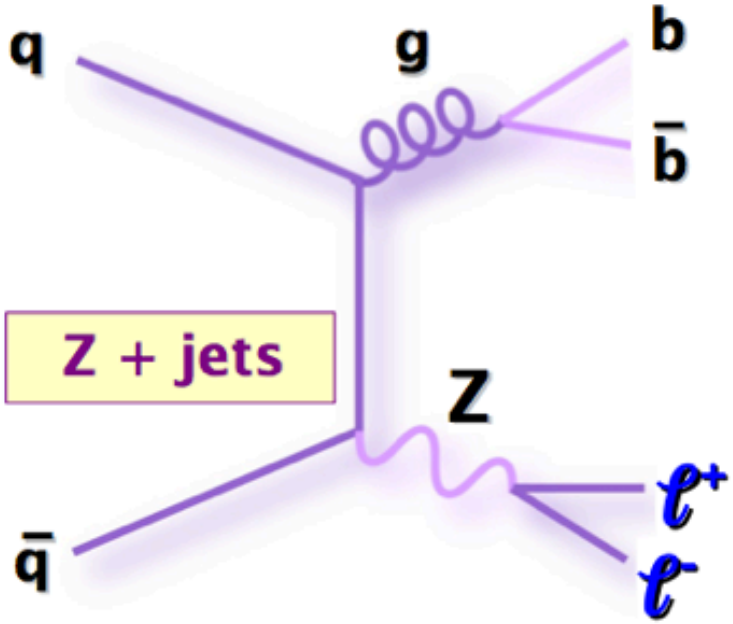
signal



ee, eμ, μμ



background

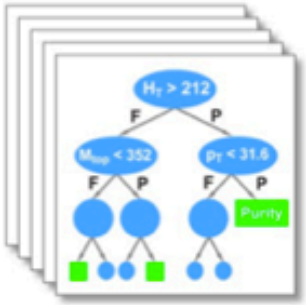


Z + jets

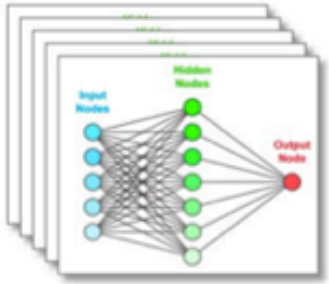
- less statistics
- less background

Multivariate Analyses

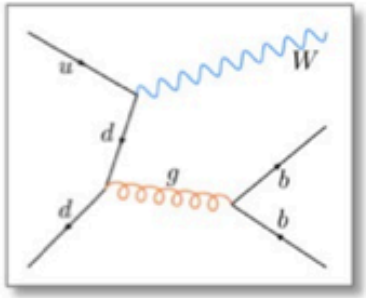
Boosted Decision Trees



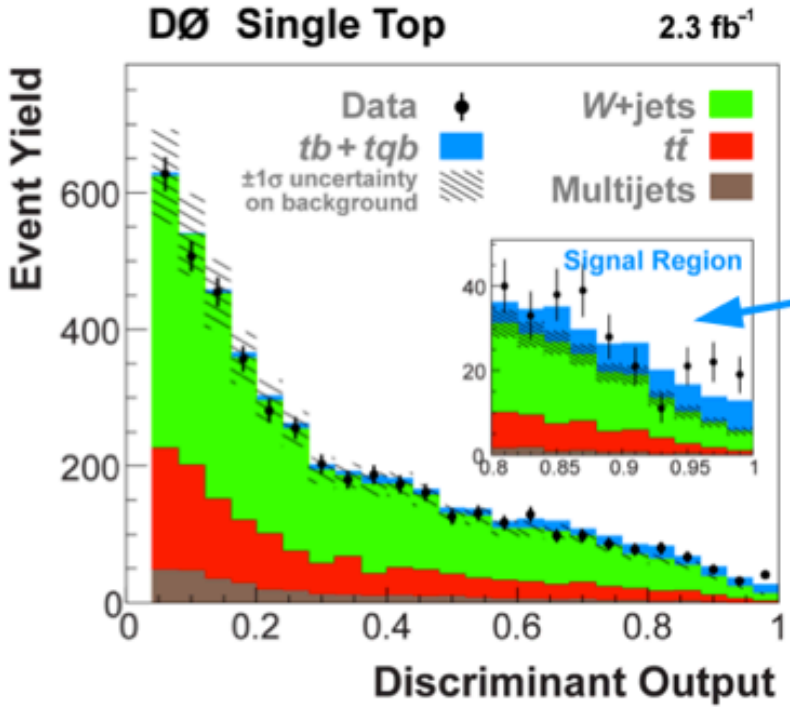
Boosted Neural Networks



Matrix Elements



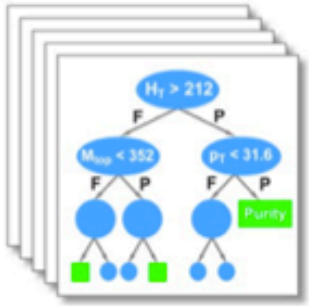
combine up to 12 different analysis channels:



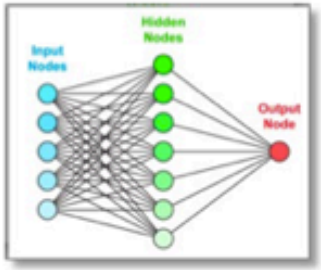
single top

Multivariate Analyses

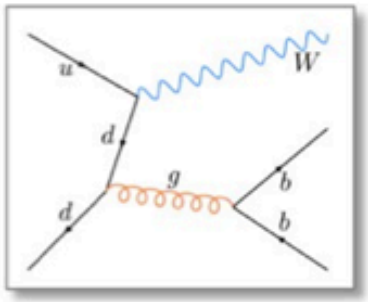
Boosted Decision Trees



Neural Networks



Matrix Elements



Likelihood

$$p_{ik} = \frac{f_{ij_ik}}{\sum_{m=1}^{5} f_{ij_im}},$$

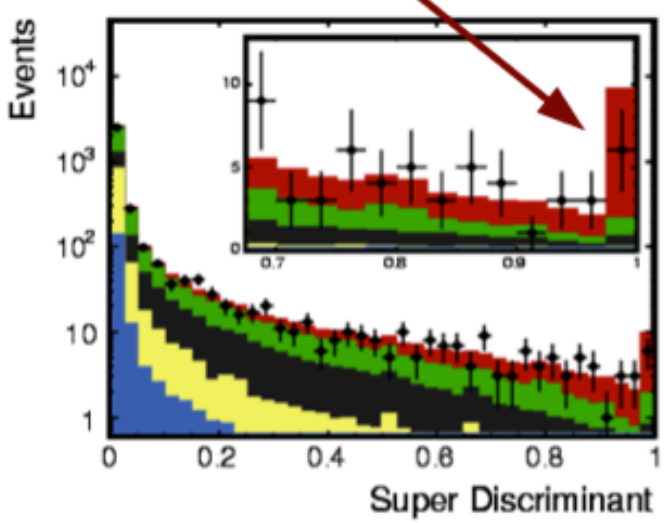
$$\mathcal{L}_k(\{x_i\}) = \frac{\prod_{i=1}^{n_{var}} p_{ik}}{\sum_{m=1}^{5} \prod_{i=1}^{n_{var}} p_{ik}}.$$

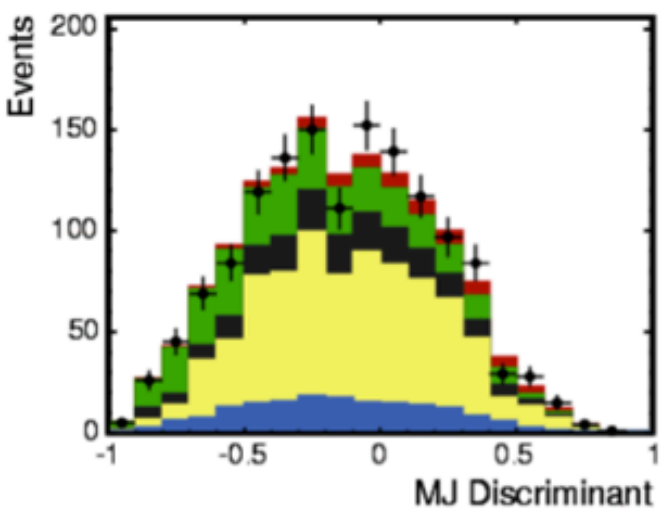
combine up to 8 different analysis channels:

single top

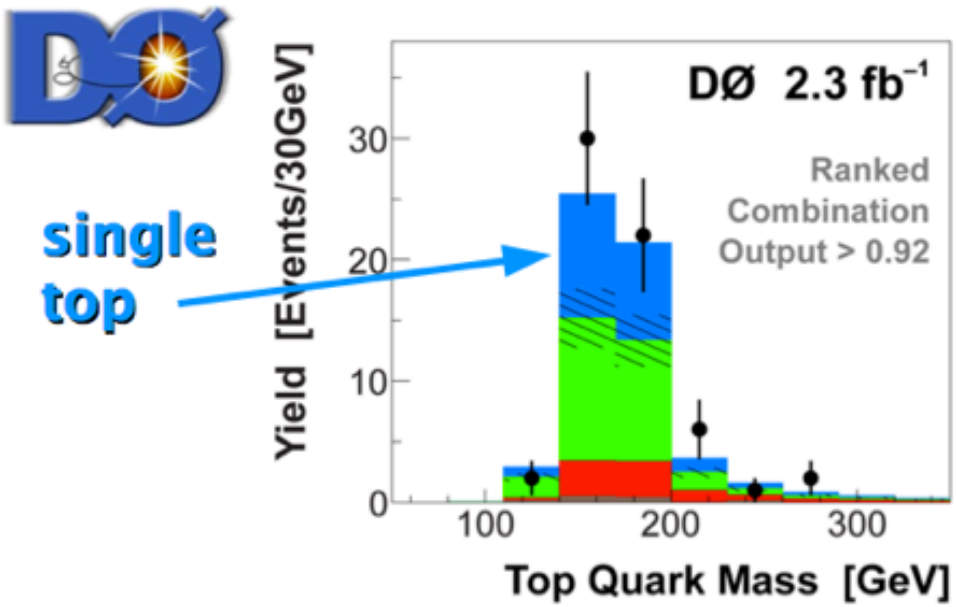
- $\not{E}_T$+jets selection :

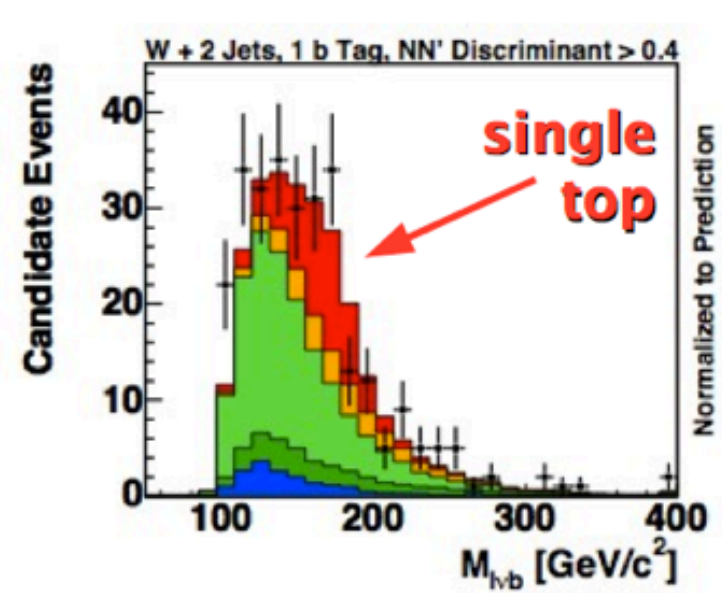
  recover badly reconstructed e, μ; include τ





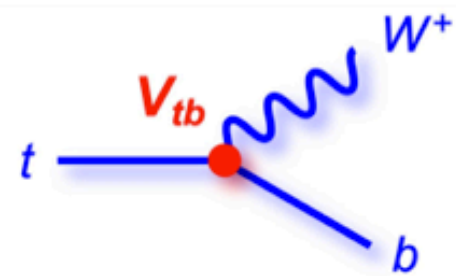
Single Top Quark Observation





Single Top Cross Section	Signal Significance Expected	Signal Significance Observed
DØ 2.3 fb^{-1} arXiv:0903.0850 m_{top} = 170 GeV		
3.94 ± 0.88 pb	4.5 σ	5.0 σ
CDF 3.2 fb^{-1} arXiv:0903.0885 m_{top} = 175 GeV		
$2.3\ ^{+0.6}_{-0.5}$ pb	>5.9 σ	5.0 σ

⇒ **observation with 5.0σ!**



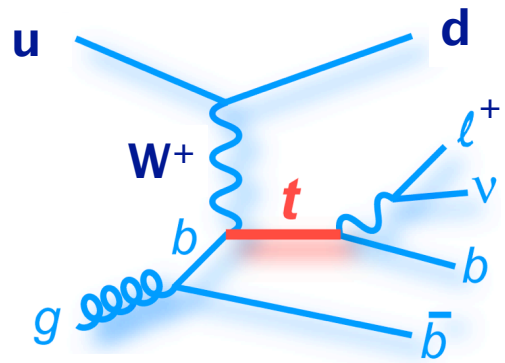
DØ: $|V_{tb}| = 1.07 \pm 0.12$

CDF: $|V_{tb}| = 0.91 \pm 0.13$

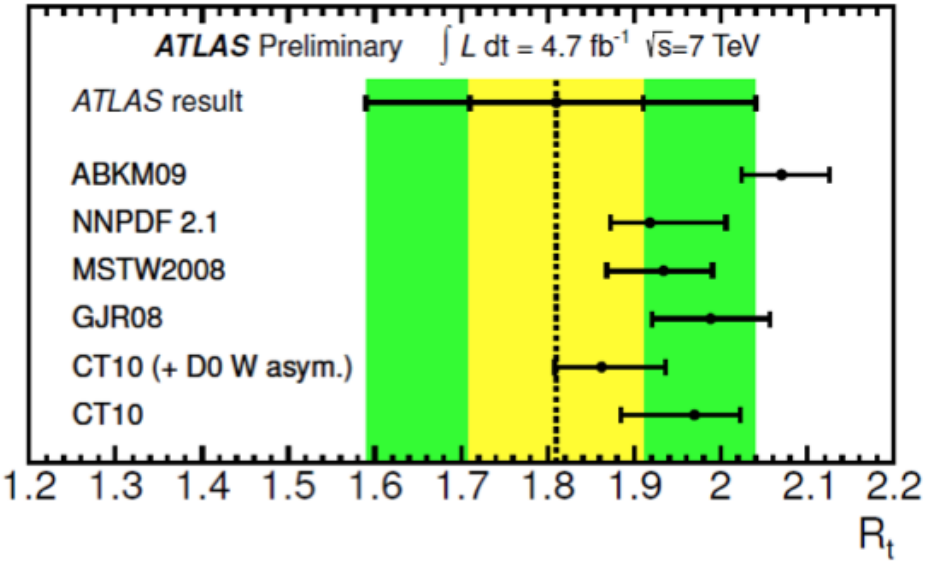
Single Top Quark Observation

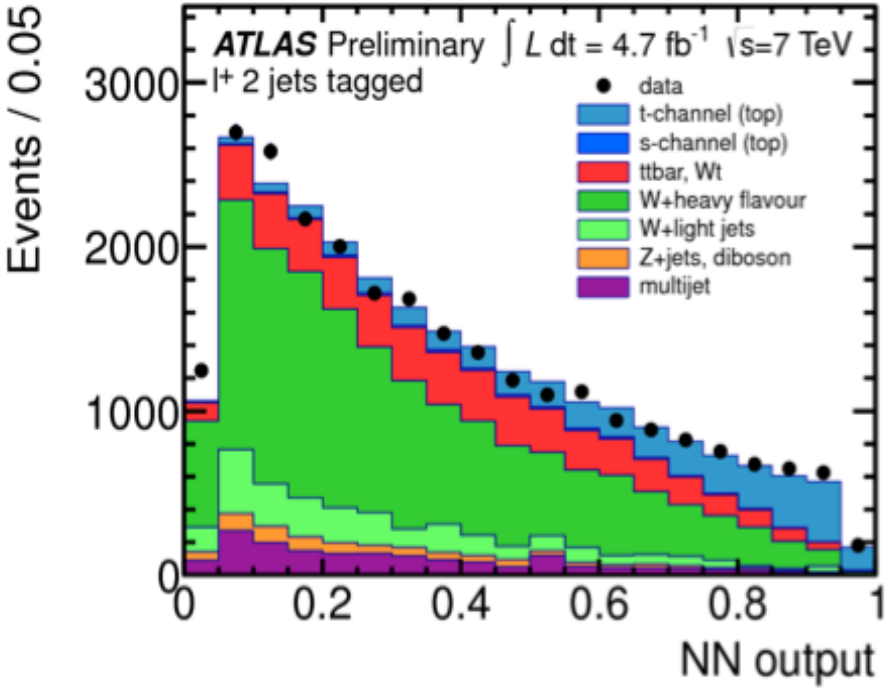
Single Top t-channel Production

- remove s/t channel constraint which could be changed by new physics
- train multivariate analysis for t-channel
- measure s- and t-channel simultaneously



check light quark flavor content of proton:





$$\sigma_t(t) = 53.2 \pm 10.8\,\text{pb}$$

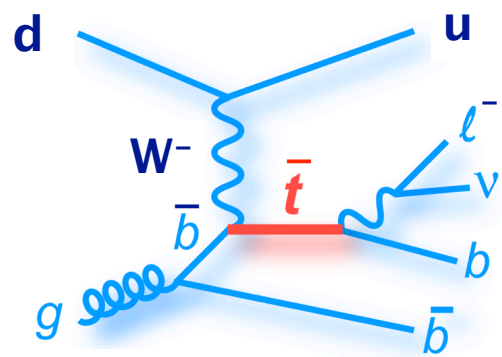
$$\sigma_t(\bar{t}) = 29.5^{+7.4}_{-7.5}\,\text{pb}$$

$$R_t = 1.81^{+0.23}_{-0.22}.$$

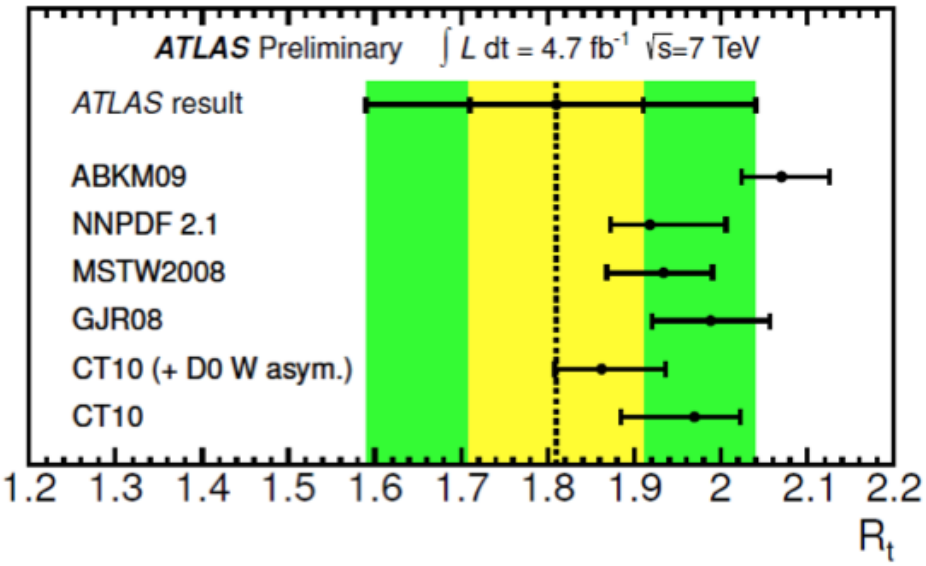
$$R_t \equiv \sigma_t(t)/\sigma_t(\bar{t})$$

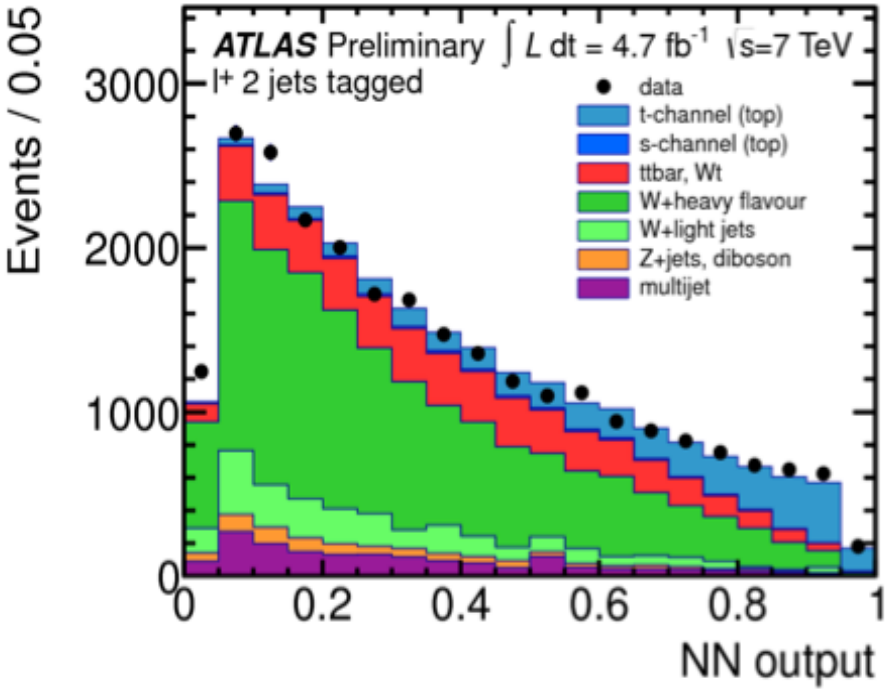
Single Top t-channel Production

- remove s/t channel constraint which could be changed by new physics
- train multivariate analysis for t-channel
- measure s- and t-channel simultaneously



check light quark flavor content of proton:





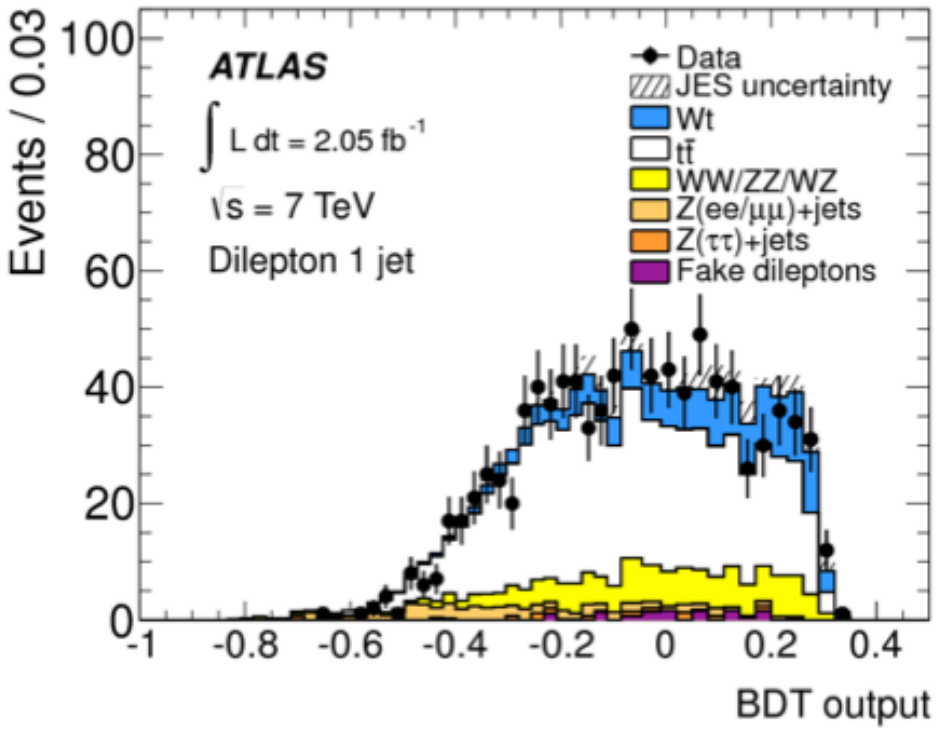
$$\sigma_t(t) = 53.2 \pm 10.8\,\text{pb}$$

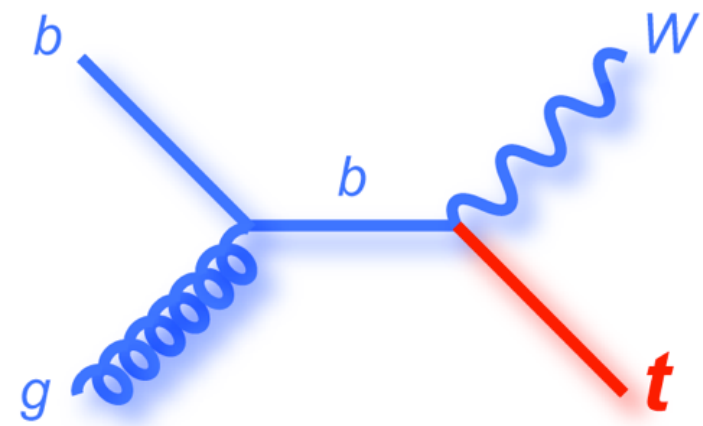
$$\sigma_t(\bar{t}) = 29.5^{+7.4}_{-7.5}\,\text{pb}$$

$$R_t = 1.81^{+0.23}_{-0.22}.$$

$$R_t \equiv \sigma_t(t)/\sigma_t(\bar{t})$$

Single Top Wt-channel Production





$$\sigma_{Wt} = 16.8 \pm 2.9\,(\text{stat}) \pm 4.9\,(\text{syst})\ \text{pb}$$

evidence with 3.3σ

SM: σ_{Wt}=15.7 pb